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# VALLEYS AND PARKS OF THE KAIBAB AND COCONINO PLATEAUS, ARIZONA

ARTHUR N. STRAHLER
Columbia University, New York City

ABSTRACT

Open valleys of the Kaibab and Coconino plateaus were interpreted by Davis, Johnson, and Robinson as mature stream valleys indicating former peneplanation in the Grand Canyon region. The writer proposes a noncyclic explanation in which limestone solution at higher, more humid elevations caused abandonment of young valleys by surface streams. Evidence supporting the latter hypothesis includes: close relationship of valley form to climate and vegetation zoning, abundant sinkholes on the Kaibab summit, absence of surface streams and the presence of slope-wash fans and fill in the open valleys, and the youthful appearance of certain streamless valleys, considered by Davis to be mature.

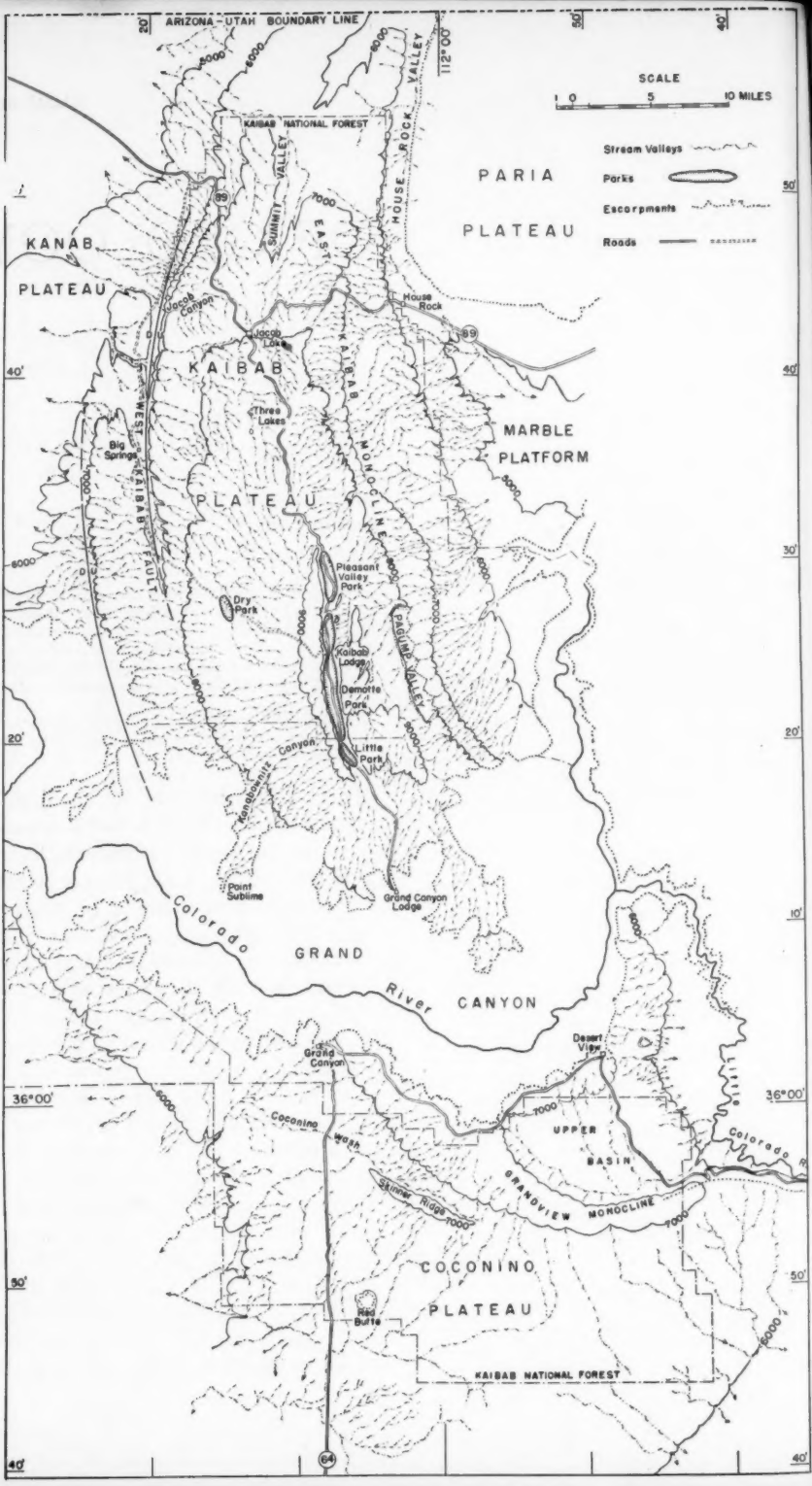
Parks of the Kaibab are elongate closed basins with abundant karst features and only insignificant exterior surface drainage. They are attributed to enlargement and deepening of earlier stream valleys by limestone solution.

## INTRODUCTION

Valleys and parks of the Kaibab and Coconino plateaus in the Grand Canyon region have attracted the attention of geologists from the time of the earliest explorations. In 1939, while studying the East Kaibab monocline,[1] the writer had the opportunity to examine some of these valleys and parks. Because of their importance in interpretations of Tertiary history of the Grand Canyon region and the finding of new evidence which casts doubt upon the validity of certain conclusions appearing in the literature, a special study of the valleys and parks was made in the summer of 1941, the results of which are stated in the present paper.

The Kaibab Plateau is a broad, asymmetrical arch underlain by the highly resistant Permian Kaibab and Toroweap limestone formations from which the overlying Triassic and Jurassic strata have been almost completely stripped (Fig. 1). The plateau surface, now rising to over 9,000 feet elevation, coincides approximately with the upper surface of the Kaibab formation. On the steeper east side the East Kaibab monocline, a great double flexure, steps the Kaibab limestone down 3,000 feet to the Marble Platform level. The Paria Plateau, which stands adjacent to the northern end of the Kaibab arch, is a remnant block of Jurassic sandstones. The Kaibab Plateau surface descends gently westward for 10 miles, then abruptly drops down to the Kanab Plateau level, 5,000–6,000 feet elevation, across the multiple West Kaibab fault (Fig. 1). Date of the East Kaibab monoclinal flexing seems to be

[1] D. L. Babenroth and A. N. Strahler, "The East Kaibab Monocline, Arizona and Utah" (manuscript in preparation for publication).


ARIZONA - UTAH BOUNDARY LINE
112°00'
SCALE
1 0 5 10 MILES
Stream Valleys
Parks
Escarpments
Roads
KAIBAB NATIONAL FOREST
PARIA PLATEAU
KANAB PLATEAU
KAIBAB PLATEAU
MARBLE PLATFORM
SUMMIT VALLEY
EAST KAIBAB MONOCLINE
HOUSE ROCK VALLEY
WEST KAIBAB FAULT
PAGINE VALLEY
Jacob Canyon
Jacob Lake
House Rock
Three Lakes
Big Springs
Pleasant Valley Park
Dry Park
Kaibab Lodge
Demotte Park
Little Park
Kanabownits Canyon
Point Sublime
Grand Canyon Lodge
Colorado River
GRAND CANYON
Grand Canyon
Desert View
Little Colorado R.
Coconino Wash
Skinner Ridge
UPPER BASIN
GRANDVIEW MONOCLINE
COCONINO PLATEAU
Red Butte
KAIBAB NATIONAL FOREST
36°00'
89
64

post-Cretaceous and pre-Eocene, or Laramide;[2] but the age of the West Kaibab fault has not yet been satisfactorily determined. The high degree to which streams have adapted themselves to the West Kaibab fault line suggests that the faulting may be relatively ancient. In this paper it is assumed that topographic features of this part of the Grand Canyon region have all been developed since the last major regional deformation. Thus the possibility of significant rejuvenation of streams by faulting or flexing is not considered.

The Coconino Plateau is the southward continuation of the Kaibab arch, from which it is separated topographically by the Grand Canyon and structurally by the Grandview branch of the East Kaibab monocline (Fig. 1). The Coconino Plateau surface is lower than the Kaibab and descends almost imperceptibly to lower levels on the west and south. On the east it is bounded by the southern part of the East Kaibab monocline. Like the Kaibab Plateau, the Coconino Plateau is underlain by the stripped Kaibab limestone.

Both the Kaibab and Coconino Plateaus are covered by an intricate system of stream valleys (Fig. 1), most of which follow closely the dip of the strata and tend to produce a subparallel drainage pattern. They are, in all probability, valleys of resequent streams. Original consequents of such small size could hardly have persisted during the removal of thousands of feet of alternately resistant and weak Mesozoic strata. A few of the streams may be subsequents developed along minor fault lines. The unusual interest in the plateau valleys lies not in the genesis or drainage pattern but in the valley forms. They are, for the most part, shallow, with flat or undulating floors underlain by a fill or waste, even up to their very heads, and rarely contain stream channels (Fig. 2). The same valleys, traced down the flanks of

FIG. 2.—Kanabownits Canyon, a typical open valley on the Kaibab Plateau. The undulating valley floor shows no surface stream. Solution sink in foreground.

[2] *Ibid.*

FIG. 1.—Map of the Kaibab and Coconino plateaus, northern Arizona. Drainage lines from U.S. Department of Agriculture, Forest Service, map of the Kaibab National Forest. Contours sketched from reconnaissance U.S. Geological Survey topographic maps of the Powell surveys.

the plateaus to lower, more arid levels, become progressively narrower bottomed until they become V-canyons being actively deepened (Fig. 3). These ultimately enter the vigorous young Colorado River. The progression from an apparently mature form near the headwaters to a youthful form downstream has seemed to some geomorphologists to be evidence of two cycles of erosion in the Grand Canyon district.

FIG. 3.—Sinuous young canyons cut into the Kaibab limestone at the base of the East Kaibab monocline south of House Rock.

FIG. 4.—Pleasant Valley Park on the Kaibab Plateau. Residual mass of magnesian limestones in foreground; east wall of park in background.

Parks of the Kaibab Plateau lie along the crest of the Kaibab arch, forming a north-south chain of elongate closed basins, totally devoid of trees but surrounded by rich forests (Figs. 1 and 4). Elsewhere on the Kaibab Plateau are smaller parks. The Coconino Plateau does not seem to have comparable park-like depressions, but some suggestion of them was seen in a few broad shallow basins. The origin and significance of the Kaibab parks is discussed separately in a section following analysis of the valley forms.

## PREVIOUS WORK

A brief geological report on the Coconino Plateau was made by J. S. Newberry,[3] who traversed it from west to east. He stated that "the surface has been considerably modified by erosion, and now presents many broad and shallow excavated valleys." A search through the reports of G. K. Gilbert[4] and J. W.

[3] "Geological Report on the Colorado River of the West," Part III of Lieutenant J. C. Ives's report of Colorado Exploring Expedition of 1857–58 (Washington, 1861), pp. 58–61.

[4] "Report on the Geology of Portions of Nevada, Utah, California, and Arizona," *U. S. Geog. Surv. West of the 100th Meridian under First Lieut. Geo. M. Wheeler*, Vol. III, Part I (1875), pp. 21–85.

Powell[5] has failed to reveal any contributions to the geomorphology of the Kaibab and Coconino plateaus, despite C. E. Dutton's[6] statement in regard to the origin of Kaibab parks that "Powell and Gilbert were at first inclined to suspect that a long, narrow wedge on the summit of the plateau had dropped between two faults. . . . . " As Dutton gave no reference to any published work, it is possible that the statements were made in oral discussion or in letters.

An investigation of the Kaibab Plateau would be seriously handicapped if it could not be based upon Dutton's monograph on the Grand Canyon district,[7] in which appears the only comprehensive description of valleys and parks of the Kaibab. Dutton's remarkably vivid word-pictures of the Kaibab and its sylvan scenery have made the region familiar to most geologists.

Dutton described the West Kaibab fault and its associated topographic forms, one of the valleys draining the western slope of the Kaibab Plateau, and Demotte Park and Little Park on the plateau summit (Fig. 1). He noted the change from a narrow canyon with precipitous walls to a broad open valley as he climbed toward the summit. One of the most significant characteristics of the Kaibab valleys he described in these words:

> And now the effect of the absence of streams becomes manifest. Not only are there no perennial brooks, but there are no indications that even in the time of heavy rains or melting snow any notable amount of water ever runs in these channels. Yet the Kaibab is a moist region. . . . . In all other plateaus or mountain ranges of equal mass and altitude and with equal precipitation there are many goodly streams, and even large creeks. . . . . But so rare are the indications of running water on the Kaibab, even in times of melting snows or of vernal rains, that whenever we find a "wash" we look at it with surprise as if it were a strange phenomenon demanding special explanation. But the very absence of these traces of running water constitutes one of the greatest charms of the Kaibab, for every ravine is smooth as a lawn and carpeted with a turf of mountain grass, richly decked with flowers of rare beauty and luxuriance.[8]

In Demotte Park, Dutton noted numerous sinkholes; those which hold water throughout the year he termed "lagoons." With some caution he suggested that the sinks connect with a system of subterranean drainage channels emerging in the heads of Grand Canyon amphitheaters.[9]

Geomorphic history of the Kaibab region as outlined by Dutton consists of the following steps:[10] (*a*) In Eocene time the region had not yet been faulted or flexed, but the Colorado River and its tributaries were already formed, having taken consequent courses on Eocene lake floors. One such tributary, especially important to our study, occupied a line represented today by the chain of axial parks. (*b*) Throughout the remainder of the Eocene and all of the Miocene the region was undergoing progressive elevation but at the same time was being denuded in a moist, warm climate. In this period, known as "the Great Denudation," nearly 10,000 feet of strata were removed. (*c*) In the Pliocene the East Kaibab monocline was formed, and with it the Kaibab Plateau arch. The deformation, together with a change to an arid climate, forced extinction of the axial Kaibab tributary to the Colorado. (*d*)

[5] "Exploration of the Colorado River of the West and Its Tributaries," (Washington: Govt. Printing Office, 1875), pp. 291.

[6] "Tertiary History of the Grand Canyon District," *U.S. Geol Surv. Mono. II* (1882), p. 193.

[7] *Ibid.*, pp. 122–39, 157–82.

[8] *Ibid.*, pp. 131–32.

[9] *Ibid.*, pp. 135–39.

[10] *Ibid.*, pp. 188–98.

Most of the small Kaibab valleys, together with minor stream valleys on adjacent plateaus, originated during a temporarily moist period during the Pleistocene, but they now carry no water. A particularly significant observation which Dutton made concerning the Kaibab valleys is that "at the present time such action [scour by running water] has entirely ceased, and it is probable that the ravines are very slowly filling up with soil and sand, and it is certain that they are not deepening." Because Dutton's studies did not take him south of the Grand Canyon, he had no opportunity to observe valleys on the Coconino and San Francisco plateaus.

W. M. Davis[11] visited the Grand Canyon region in 1900 with the purpose of re-examining the geomorphic phenomena described by Powell and Dutton and reconsidering certain of their conclusions. One of Davis' most significant conclusions, now generally accepted, is that the East Kaibab monocline and arch are early Tertiary structures and antedate development of the drainage. Davis' route of travel took him across the Kaibab Plateau in the vicinity of Jacob Lake (Fig. 1), where topography, vegetation, and climate resemble those of the Coconino Plateau but are quite different from conditions on higher parts of the Kaibab farther south. He thus failed to see the principal parks or the true character of the higher Kaibab valleys. Nevertheless, his conclusion that the drainage lines are not antecedent required him to modify Dutton's hypothesis that the ancient axial Kaibab stream was abandoned because of crustal deformation. Instead, Davis postulated the development of a series of anticlinal valleys while the Kaibab arch was being denuded of its cover of Triassic and Jurassic strata.[12] With retreat of the sandstone cliffs down the flanks of the arch and the appearance of the Kaibab limestone to form a new topographic arch, the axial drainage lines were dismembered.

Davis was first to describe in detail the form of valleys on the Coconino Plateau.[13] He writes:

> The limestone capping of these plateaus is maturely dissected. Broad-floored, well-graded valleys with gently sloping sides ramify through the uplands in the most perfect manner; presenting a maturely developed form even to their heads; and this in spite of the fact that they are nearly always dry. . . . . Our party saw these well-established drainage ways both north and south of the main canyon, and we were much impressed with the maturity of their graded sides and floors, in contrast to the youthful expression of the precocious canyon.

From his observations Davis concluded that the "mature valleys," as he termed them, must have been formed at the close of a prolonged cycle of erosion, the "Plateau cycle," in which the Grand Canyon region was peneplaned. With rejuvenation in the present or "Canyon cycle," the lower stream courses have been incised and now possess young valleys; but on the plateaus streams have not yet been affected.

In 1906 Douglas Johnson[14] retraced Davis' route across the Kaibab Plateau in the vicinity of Jacob Lake (Fig. 1). As additional evidence of the two-cycle erosional history, Johnson described differences in dissection on the upper and lower parts of the East Kaibab monocline near House Rock (Fig. 1). On the

[11] "An Excursion to the Grand Canyon of the Colorado," *Bull. Mus. Comp. Zool.*, Vol. XXXVIII (1901), pp. 108–201.

[12] *Ibid.*, pp. 155–58.

[13] *Ibid.*, pp. 120–21.

[14] "A Geological Excursion in the Grand Canyon District," *Proc. Boston Soc. Nat. Hist.*, Vol. XXXIV (1909), pp. 135–61.

upper part of the monocline, which is here a double flexure with a flat tread between, streams are closely spaced and all flat interstream divides have been consumed, whereas on the lower fold streams are fewer, but occupy deeper, more youthful gorges, separated by broad undissected areas. Moreover, in their upper courses on the plateau above, the streams occupy mature valleys. These relationships seemed, to Johnson, to require two cycles of erosion. In a recent paper[15] the present writer has offered a simple, noncyclic explanation of the same group of facts.

Another point of evidence supporting Davis' scheme of cyclic development was found by Johnson[16] in the characteristics of Jacob Canyon (Fig. 1), mature and open at its head (Fig. 10) but progressively more youthful downstream to the point where it debouches from the West Kaibab fault-line (?) scarp. The transverse canyon profile, as seen in the scarp, consists of a narrow gorge incised into a broad upper valley. Because of the asymmetrical position of the narrow valley with respect to the center of the broad upper portion, Johnson was inclined to interpret the composite profile as the result of two cycles of erosion.

In 1910 H. H. Robinson[17] described an extensive system of shallow valleys of thoroughly mature form on the San Francisco Plateau, or southward extension of the Coconino Plateau, in the vicinity of Flagstaff and the San Francisco Peaks. These valleys are similar to those on higher parts of the Coconino Plateau nearer the Grand Canyon and occur at about the same elevation, 7,000 feet. Robinson proposed a new erosion cycle for their development. His reason for postulating two cycles, where Davis and Johnson required only one, seems to be that Robinson believed the Plateau cycle peneplane was an almost perfectly plane surface, beveling with remarkable precision both the resistant Permian limestones and the weak Triassic shales. The late-mature topography of the present Kaibab, Coconino, and San Francisco plateaus, he reasoned, must therefore have been produced in a succeeding cycle, not carried so far toward completion.

Thus the studies of Davis, Johnson, and Robinson led all three to attach cyclic significance to valleys of the Coconino, Kaibab, and San Francisco plateaus. None of these men seems to have had opportunity to study the higher parts of the Kaibab Plateau, whereas Dutton worked largely on the higher Kaibab and did not observe the plateaus south of the Grand Canyon.

## ANALYSIS OF THE PROBLEM OF VALLEY DEVELOPMENT

### HYPOTHESES OF ORIGIN

*Hypothesis of desiccation.*—Dutton's hypothesis of origin for open Kaibab valleys may be restated as follows:[18] At the close of the arid Pliocene epoch the Kaibab arch of Permian limestone stood denuded of its Mesozoic cover, with much the same regional geologic and topographic conditions as exist today. The period of aridity and deformation had witnessed extinction of the axial Kaibab stream and presumably all other lesser streams on the plateau and adjacent areas. With a marked increase in

[15] Strahler, "East Kaibab Monocline and Kaibab Plateau—Jacob Lake Quadrangle, Arizona," *Jour. Geomorph.*, Vol V (1942), pp 178–80.

[16] Pp. 147–48 of ftn. 14 (1909).

[17] "A New Erosion Cycle in the Grand Canyon District, Arizona," *Jour. Geol.*, Vol. XVIII (1910), pp. 742–63.

[18] Dutton, ftn. 6 (1882).

precipitation accompanying Pleistocene continental glaciation, numerous streams came into existence on the Kaibab Plateau, as well as on the lower Marble Platform, Kanab Plateau, and Paria Plateau. During the brief period of their activity the streams cut narrow valleys, but with a return to present conditions of greater aridity the valleys were deserted and began to fill with soil and slope wash from the valley walls.

The difficulties which confront Dutton's hypothesis have been treated by Davis.[19] The belief that today streams are not actively carving the smaller valleys of the Grand Canyon region is discredited by Davis, who cites examples of stream channels in the ravines at the East Kaibab monocline base and in House Rock valley, which "bear every mark of being strongly flushed by occasional wet-weather floods." Students of the region today will indorse Davis' conclusion that valleys in the lower flanks of the Kaibab and Coconino plateaus and in the Marble Platform and Kanab Plateau are being vigorously corraded. If there is sufficient rainfall for this activity at the relatively more arid lower levels of the region, how could a lack of precipitation be held responsible for absence of active streams on the higher and better-watered Kaibab Plateau? Dutton's reasoning thus fails to explain his own accurate observations on the form and character of the open Kaibab valleys. Nevertheless, it is reasonable to suppose that a somewhat moister Pleistocene epoch resulted in generally accelerated stream activity for the region as a whole. A period of great landsliding along the Vermilion and Echo cliffs of the near-by Paria and Kaibito plateaus, best explained as resulting from increased precipitation in the Pleistocene, has been described by the writer.[20]

*Hypothesis of mature stream valleys.*—The hypothesis proposed by Davis and supported by further findings of Johnson and Robinson[21] can be restated as follows: In late Tertiary time (Pliocene?), after all major deformation had been completed, there developed over the Grand Canyon region a peneplane, the end product of the Plateau cycle of erosion. From various points in Davis' discussion it may be supposed that the peneplane stood at about the present 6,500-foot level and that the weak Triassic rocks on which the surface was developed covered both the Kanab Plateau and Marble Platform (Fig. 1). Rising above the peneplane level as monadnock masses were the Kaibab and Coconino plateaus. At the West Kaibab fault line, Triassic shales were in contact with the Permian limestones of the upthrow block and covered most of the scarp which we see today. On the east side of the Kaibab Plateau shales covered the lower fold of the double monocline. The Coconino Plateau limestone area was relatively small, perhaps not extending more than 10 miles south from the present Canyon rim. The San Francisco Plateau in the vicinity of Flagstaff may also have risen somewhat above a surrounding peneplane on weak shales. Streams on all of the higher limestone masses had dissected the land to a stage of late maturity, the streams themselves having reached maturity almost to their heads, while valley walls had weathered to gentle slopes.

A general uplift of the region then en-

[19] P. 192 of ftn. 11 (1901).

[20] Strahler, "Landslides of the Vermilion and Echo Cliffs, Northern Arizona," *Jour. Geomorph.*, Vol. III (1940), pp. 285–301.

[21] Davis, ftn. 11 (1901); Johnson, ftn. 14 (1909); Robinson, ftn. 17 (1910).

sued, causing the Colorado River and its principal tributaries to be rejuvenated and to incise deep gorges. As the new cycle or "Canyon cycle" continued, rejuvenation progressed steadily up the tributary systems until the lower ends of the valleys on both flanks of the Kaibab arch and on the abrupt eastern margin of the Coconino Plateau reverted to the steep-walled, narrow forms of youth. In this stage we find the region today. The upper stream courses on higher parts of the Kaibab, Coconino, and San Francisco plateaus have not yet felt the effects of the new cycle.

The significance of Davis' hypothesis for the formation of mature valleys is particularly great because, if valid, it has a bearing on erosional history of the entire Grand Canyon region. Indeed, Davis, Johnson, and Robinson all seem to have regarded the valley forms as providing perhaps the strongest evidence of peneplanation to be found in the region. Critical treatment of the hypothesis of mature valleys will, however, be deferred until a new hypothesis is outlined. The two will then be subjected, side by side, to deductive analysis.

*Hypothesis of valley abandonment resulting from limestone solution.*—Field study of the higher Kaibab Plateau has permitted the writer to verify almost all of the facts emphasized by Dutton regarding the valleys and parks, which, because they are not found along the route traveled by Davis or Johnson and were far outside the area studied by Robinson, were not taken into consideration by the later workers. Some of Dutton's significant facts, together with new ones observed by the writer, include: the absence of stream channels in many of the valley floors; the irregularity of valley-floor gradients, not uncommonly reversing the down-valley slope; abundant sinkholes, both in the valleys and parks and in the uplands between; alluvial fans built out across the valleys; absence of stream-laid materials wherever excavations or minor gullies in the valley floors permitted examination of the fill, which, instead, consists of unsorted slope wash; and the remarkable correlation between the degree of development of these various features and the various climatic zones in which they lie. Not only do some of these facts seem unexpected under Davis' mature-valley interpretation, but they suggest a new hypothesis, stated below.

During the denudation of the Grand Canyon region of its Mesozoic cover in later Tertiary time, the Permian Kaibab limestone was first uncovered along the axis of the Kaibab arch where it now stands highest, in the vicinity of Demotte Park (Fig. 1). The Kaibab Plateau thus came into existence at an earlier date than most of the surrounding topographic units and has for a long period stood higher than any other part of the Grand Canyon region. While being stripped of the Mesozoic shales and sandstones, the Kaibab began to be scored by innumerable resequent streams following the easterly or westerly dip of the strata. Because of its superior elevation, the Kaibab must have caught a large supply of orographic precipitation, which, combined with lower temperatures of the higher altitude, gave a humid climate. The Coconino and San Francisco plateaus were similarly uncovered and dissected, but at a later date. Moreover, their lower elevation allowed them less precipitation than the Kaibab Plateau.

By the time higher parts of the Kaibab had been maturely dissected, with a relief of about 200 feet but with the stream valleys still young and being vigorously corraded (Fig. 5), a new process began to

make its effects apparent. Ground water percolating through the soluble Kaibab and Toroweap limestones and finding easy passage through the permeable Coconino sandstone to the Grand Canyon walls subtracted increasing amounts from the surface drainage. One by one, the surface streams became broken into tiny units, each one underfit and incapable of removing the accumulation of slope wash brought down the valley walls or from lesser tributary gullies. With the further accumulation of debris, such surface streams as did survive lost most or all of their volume to subsurface flow in the valley fill (Fig. 6). Slope-wash fans were built out across the valleys, causing local reversals in the normal gradient of the valley bottoms. Valley walls accumulated a more gently sloping cover of soil and rock debris through which only the more resistant limestone strata protruded (Fig. 7).

The conversion from surface to subsurface drainage, with resultant abandonment of the valleys, progressed from the highest parts of the Kaibab, down its flanks, to lower levels. Because of the rapid decrease in precipitation at progressively lower elevations, the effects of solution were largely limited to the higher parts of the plateaus. On the lower northern end and western flank of the Kaibab Plateau and on the Coconino and San Francisco plateaus a transitional stage (Fig. 6) is present between the young valleys (Fig. 5) at lower elevations and the greatly modified valleys of the highest parts of the Kaibab (Fig. 7). The process outlined above is active today.

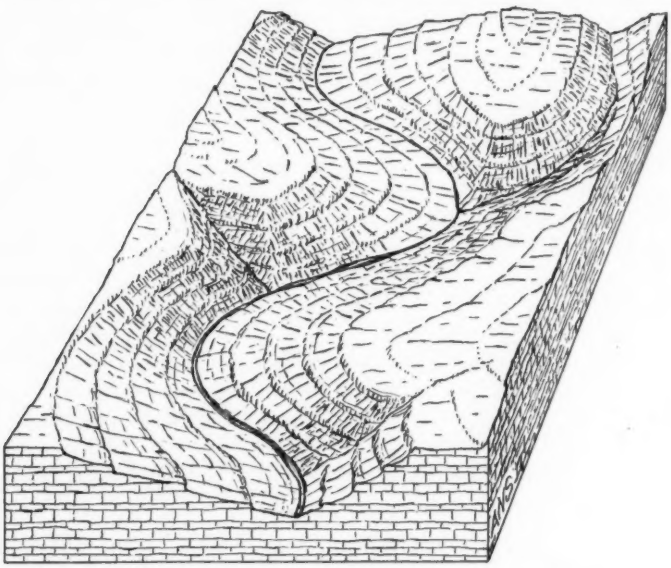


FIG. 5.—Young valley in Kaibab and Toroweap limestones

The new hypothesis requires no multiple erosion cycles. A single, slow uplift of the region or a succession of intermittent uplifts with no prolonged period for peneplanation seems an entirely ade-

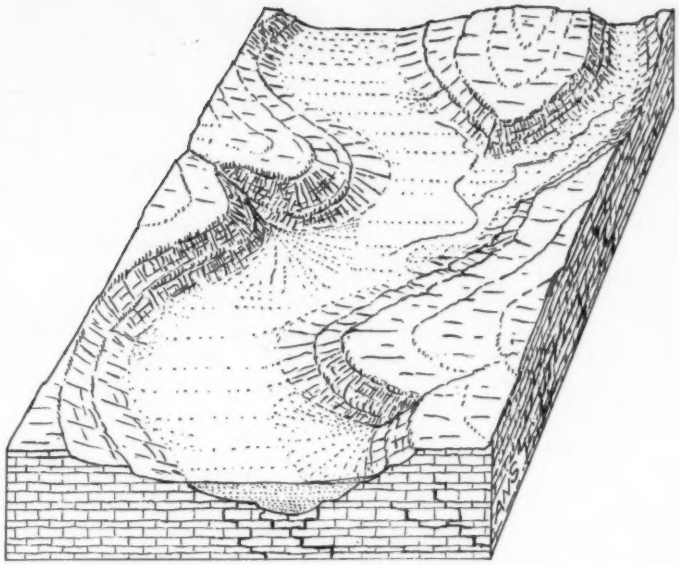


FIG. 6.—Abandoned valley partly filled with waste from the valley walls. Characteristic of valleys on the Coconino Plateau.

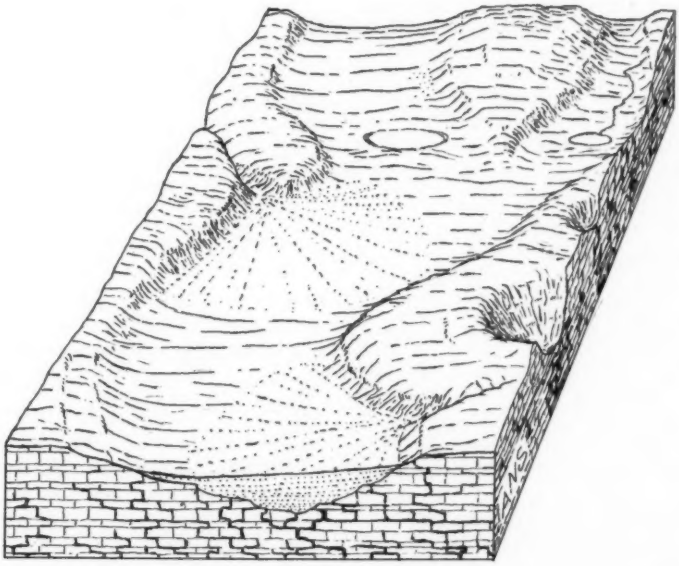


FIG. 7.—Abandoned valley in advanced stage of decay. Undulating floor has numerous slope-wash fans and shallow sinks. Bare rock is largely concealed. Deep sinkholes are eaten into interstream areas. Typical of Kaibab Plateau above 8,000 feet elevation.

quate postulate to accompany the hypothesis.

TESTING OF THE TWO MAJOR HYPOTHESES

The last two hypotheses of origin of open valleys on the Kaibab and Coconino plateaus outlined above will be treated according to the analytical method of investigation and presentation.[22] Expected consequences of each hypothesis will be determined and then confronted with the field facts. This treatment will bring many specific points of field evidence into direct association with the theoretical deductions to which they apply.

*Evidences of limestone solution.*—If the hypothesis of valley abandonment through diversion to underground drainage is correct, there should exist independent evidence of extensive limestone solution throughout the higher parts of the plateaus and evidence that considerable water flows through subterranean channels. On the other hand, the hypothesis of mature valleys does not require these evidences of solution, although it is possible that they could be superimposed upon a system of mature valleys. This test cannot, therefore, serve to eliminate the hypothesis of mature valleys; but it is critical to the validity of the hypothesis of abandoned valleys.

The most obvious proof of extensive limestone solution lies in the abundant sinkholes distributed over the surface of the Kaibab Plateau above 8,000 feet elevation. Many of these are shown on topographic maps of the Grand Canyon National Park and the Jacob Lake quadrangle.[23] Sinks which occur in the valley floors (Fig. 2) and in parks (Figs. 12 and 13) are generally shallow and often contain pools of water, termed "lagoons" by Dutton. In a few cases this type of sink might be confused with depressions produced between slope-wash fans built across the valleys. The deepest sinkholes occur on the spurs and divides between valleys and parks. They are deep, bowl-shaped or conical depressions such as those shown on the right-hand edge of the block diagram, Figure 7. The most impressive sinkhole of this type observed by the writer is located about 1 mile north of Three Lakes (Fig. 1). It is over 200 feet deep.

Topography of the floor of Pleasant Valley Park (Figs. 1 and 4) is strongly suggestive of the dominant role of solution at the summit of the Kaibab arch. Irregularly shaped blocks of limestone, about 50–100 yards across, stand above the general level of the park floor, their edges forming scarps several feet high (Fig. 4). The strata are variously tilted and are sometimes turned down near the margins. Between the blocks are irregular undrained depressions and sinkholes. The ensemble might be correctly termed "karst topography."

The possibility that the limestone blocks have settled downward through a considerable distance, due to removal of more soluble rock beneath, is suggested by differences in lithology and faunas of adjacent masses. One mass in particular (Fig. 4) seems far below its original stratigraphic position in relation to the rock series outcropping in the park walls. It answers to the description of the highest, or $\alpha$, member of the Kaibab formation,[24] which has been generally stripped from the more resistant members beneath over the rest of the Kaibab

[22] Johnson, "Studies in Scientific Method," *Jour. Geomorph.*, Vol. III (1940), pp. 156–62, 256–62.

[23] Strahler, ftn. 15 (1942).

[24] E. D. McKee, "The Environment and History of the Toroweap and Kaibab Formations of Northern Arizona and Southern Utah," *Carnegie Inst. of Wash. Pub. No. 492* (1938), pp. 50–54.

Plateau. The rock is a thin-bedded, hard, magnesian limestone of brown to buff color, with a pitted surface. Beneath this are some thin-bedded red shales and sandstones, such as are usually found between the $\alpha$ and $\beta$ limestones. Fossils collected included such genera as *Bellerophon*, *Plagioglypta*, and *Euomphalus*, which are characteristic of the $\alpha$ fauna. If the identification of this rock as $\alpha$ limestone is correct, the mass now lies more than 200 feet below the corresponding horizon in the rock series on either side of the park. Down-faulting seems inadequate to explain the position of the limestone masses in the floor of Pleasant Valley Park, because of the small size of the blocks and the intricate and irregular fault pattern which would be necessary. Slumping from the park walls is a possibility to be considered, but the notable absence of slumping in the Kaibab and Toroweap cliffs throughout the Grand Canyon region would make this an unusual case. Furthermore, the masses are not tilted strongly or consistently toward the park walls, as would be expected of rotated slump blocks.[25] The inadequacy of alternate explanations for the limestone masses on the park floor and the presence of many sinks strongly favors the conclusion that a great amount of limestone has been removed by solution along the axis of the Kaibab arch and that some less soluble masses have slowly settled to the present level of the park floor.

Both the lithology and structure of the Kaibab Plateau seem highly favorable for the disposal of ground water. Beneath the soluble Kaibab and Toroweap formations lies the Coconino sandstone, a pure cross-bedded aeolian sand formation. Under the Coconino lie the Hermit and Supai shales and sandstones, probably less pervious than the overlying rocks. The anticlinal structure of the Kaibab Plateau, with dips east and west from the axis, and the pitch of the axis southward toward the Grand Canyon from a point near Demotte Park and northward into Utah from the same point should facilitate the motion of subsurface waters toward the margins of the plateau. Springs, many of which supply copious amounts of water throughout the year, emerge from the plateau margins wherever Permian and older strata are exposed in cliffs. Several such springs are shown on the Grand Canyon topographic map. Dutton writes of "Tapeats Creek, a considerable stream of clear water fed by many large springs bursting from the lower portions of the great Kaibab wall," and elsewhere describes a spring of water issuing from the lower Aubrey (Coconino) sandstone in the Muav saddle.[26] L. F. Noble states:

> . . . . the water that sinks underground—which far exceeds the surface water in quantity because of the system of caves, sink holes, and underground drainage channels with which the Kaibab limestone is honeycombed—eventually finds its way southwestward along the dip of the strata and reappears as springs in the northern wall of the Grand Canyon, feeding the tributary streams of the Colorado and increasing the activity of the forces of erosion on that side of the river.[27]

Roaring Springs, which issues from a cavern in the Muav limestone near the head of Bright Angel Canyon, increases in volume in the early months of spring while the snows on the Kaibab Plateau above are melting.[28] A copious spring issues from strata exposed in the south-

[25] Strahler, ftn. 20 (1940).

[26] Dutton, pp. 158, 163 of ftn. 6 (1882).

[27] L. F. Noble, "The Shinumo Quadrangle," *U S. Geol. Surv. Bull. 549* (1914), pp. 26–27.

[28] E. F. Seagle, "Exploration of Roaring Springs Cave," *Grand Canyon Nature Notes*, Vol. IX, No. 12 (1935), pp. 391–94.

ern end of Pagump Valley (Fig. 1) on the east side of the Kaibab Plateau; another from the Supai beds in the West Kaibab fault-line scarp at Big Springs (Fig. 1) on the western side of the plateau. No special study was made of the number, location, and volume of springs; but the examples described above should suffice to demonstrate the flow of considerable volumes of water beneath the Kaibab Plateau.

At lower elevations on the Kaibab Plateau and on the Coconino and San Francisco plateaus independent evidence of extensive solution is scarce. Occasionally small sinks are found, while some of the valleys include broad, shallow basins of irregular outline, suggestive of solution origin rather than stream erosion. The relative scarcity of obvious solution forms in these areas is expectable because of the lower elevation and consequent greater aridity.

*Relation of valley form to climate zones.*—Under the hypothesis of valley abandonment resulting from limestone solution there should be an excellent correlation between valley form and climate. Heavy precipitation, combined with low temperatures which reduce evaporation, would provide the most favorable conditions for solution. Low temperatures would permit greater amounts of carbon dioxide to be dissolved in the percolating waters, perhaps thereby increasing carbonation. Greater humidity would favor heavier forest and grass cover, which, in turn, would impede runoff and permit more water to enter the ground. Because higher elevation of the land brings about the increased precipitation and lower temperatures, valley form should be found to vary with altitude. Furthermore, because vegetation forms vary consistently with the climate, there should also be found a close correspondence between valley forms and vegetation zones.

Under the hypothesis of mature valleys there should be a general correspondence between valley form and elevation, inasmuch as it was postulated that only the Kaibab limestone masses now above about 6,500 feet were exposed above the peneplane. The correspondence of valley forms with climate and plant zones should, however, be only coincidental—not a close genetic association, such as the newer hypothesis requires.

The highest parts of the Kaibab Plateau, above the 8,000- or 8,250-foot contour (Fig. 1), lie in a distinctive zone of climate and vegetation known as the "Douglas fir zone,"[29] in which average annual precipitation ranges from 22 to 34 inches. A considerable part of this is in the form of snow, which accumulates during the winter to depths of more than 10 feet and remains late in the spring. Convectional rainstorms are of almost daily occurrence throughout much of the summer. The characteristic forest of this zone consists of Douglas fir and quaking aspen. The firs form dense stands between the open parks and valleys, while the aspen groves border the parks or occupy parts of the valley floors. Near the lower limits of the zone a mixture with western yellow pine sets in, while near the upper part and on north-facing slopes Engelmann spruce becomes included.[30] The soil is moist and covered by forest litter. In the open parks and valleys grasses and flowers grow freely, but not so thickly as to form a protective sod cover. The area included in the Douglas fir zone extends from the Grand

[29] G. A. Pearson, "Forest Types in the Southwest as Determined by Climate and Soil," *U.S. Dept. Agric. Tech. Bull. No. 247* (1931), pp. 9–12.

[30] *Ibid.*, pp. 9–14.

Canyon rim between Point Imperial and the Shinumo Amphitheater head northward almost to Jacob Lake (Fig. 1). On the east the zone ends abruptly just below the brow of the uppermost flexure of the double East Kaibab monocline. On the west the edge is not sharply defined because of the gentle plateau slope but lies approximately along the 8,000-foot contour shown on Figure 1.

Within the Douglas fir zone, topographic forms are distinctive. The axial chain of parks and other smaller parks are found almost exclusively in this zone. The valleys are characterized by the merging of valley sides with floors in sweeping curves and a mantle of soil and rock waste which largely obscures the bed rock (Fig. 2). The valley floors have an undulating or rolling appearance caused by slope-wash fans built across them (Figs. 7 and 11) and by numerous sinks, many of which hold water (Fig. 2). Stream channels are conspicuously absent except for occasional tiny rills which flow only short distances before ending in sinks.

Below the Douglas fir zone lies the western yellow pine zone,[31] between 7,000 and 8,000 or 8,250 feet. The annual precipitation ranges from about 18 inches in the lower part to about 25 inches near the top. Relatively pure open forests of western yellow pine characterize the zone, but there is a complete gradation both upward and downward into adjacent forest zones. Regions covered by the open western yellow pine forest are widely separated. On the Kaibab Plateau it is most conveniently observed in the vicinity of Jacob Lake, a highway junction and camping ground (Fig. 1). From here it extends southward as a narrow strip on the flank of the East Kaibab monocline to the Grand Canyon.

[31] *Ibid.*, pp. 7–9.

On the west side of the plateau the zone is a fairly broad strip, trending southward to the Canyon and roughly including the area between the 7,000- and 8,000-foot contours shown on Figure 1. The highest part of the Coconino Plateau, bordering on the south rim of the Grand Canyon, also lies within this zone. It is developed between Grand Canyon Village and the Grand View monocline, along the Canyon rim, and extends a short distance south of Skinner Ridge (Fig. 1). Much of the San Francisco Plateau south of Flagstaff is likewise included in this zone.

Not only is the form of valleys in the western yellow pine zone similar for all the three regions it includes, but the valleys are readily distinguished from those of the Douglas fir zone above and the pinyon-juniper zone below. The valleys are characterized by almost flat floors, from which the valley walls rise abruptly (Figs. 6, 8, and 9). In contrast with the higher Kaibab valleys, no sinks were seen in the floors, and alluvial fans are not so conspicuous. The ratio of width of flat floor to width of valley varies considerably for different valleys and for different parts of the same valley. For example, Coconino Wash (Fig. 1), 6 miles south of Grand Canyon Village, changes within a distance of 4 miles from a narrow canyon with high walls and narrow flat floor (Fig. 8) to a relatively broad, open valley with wide, flat floor and low valley walls (Fig. 9). In most instances the valley walls are steep (20°–25°) and the harder limestone layers form conspicuous ledges. Were it not for the flat floors, lacking stream channels, many of these valleys would be described as youthful. Indeed, the presence of strongly contrasting slip-off and undercut slopes at the bends of some of these sinuous valleys (Fig. 8) gives one

the strong impression that they have only recently been abandoned by vigorous young streams.

Below the western yellow pine zone is the woodland or pinyon-juniper zone,[32] lying between 5,000 and 7,000 feet. Annual precipitation is 12–20 inches, and temperatures average considerably higher than in the upper zones. Between 6,000 and 7,000 feet the woodland zone is characterized by a thin forest of juniper and pinyon with open areas of sagebrush. Below 6,000 feet desert conditions begin to prevail, and the forest thins rapidly, becoming supplanted by sage, cactus, and yucca.

FIG. 8.—Coconino Wash near Skinner Ridge on the Coconino Plateau. Except for the filling of slope wash in the valley bottom and the absence of any stream channel, it may be described as a youthful, sinuous canyon. Slip-off slope on left; undercut slope on right.

FIG. 9.—Coconino Wash near Highway 64, 4 miles down-valley from locality shown in Fig. 8. Valley floor is broad and flat, but walls rise abruptly and are relatively steep.

Areas covered by the pinyon-juniper forest zone include: the tread between the two flexures of the East Kaibab monocline and most of the lower flexure; the northern end of the Kaibab Plateau, from Summit Valley to the Arizona-Utah boundary line; a strip extending

[32] *Ibid.*, pp. 5–6.

along the West Kaibab fault from U.S. Highway 89 to Big Springs, then offsetting westward to the western fault line and continuing south to the Grand Canyon rim; the eastern part of the Coconino Plateau, including the Upper Basin and the area to the south and east of it; a broad area between the Coconino Plateau and the San Francisco Peaks volcanic field; and the south rim of the Grand Canyon west of Grand Canyon Village (Fig. 1).

In the pinyon-juniper zone, as well as in still lower zones, valleys cut in the Permian Kaibab and Toroweap limestones are youthful and contain active, ungraded wet-weather streams (Fig. 5). Valley walls are steep, and bedrock is everywhere exposed (Fig. 3). Bedrock floors the channels, a condition not seen in valleys of the western yellow pine and Douglas fir zones. Although the valleys are narrower and deeper on the flanks of the East Kaibab monocline than where the strata are nearly horizontal, the essential characteristics are independent of structure.

The observations stated above, illustrating the close relationship between valley form and climate zone, serve to strengthen greatly the hypothesis of abandoned valleys resulting from limestone solution under which the relationship is a vital one. A coincidence of the open valley form with the highest parts of the plateaus is also expectable under Davis' hypothesis of mature valleys, but the recognition of three valley types corresponding with three climate zones is not an expected consequence of that hypothesis; it is, instead, an unexpected difficulty not explainable solely by two erosion cycles.

*Longitudinal and transverse valley profiles.*—Under the two hypotheses being considered, longitudinal profiles of the valleys would be expected to show distinct and important differences. If development has proceeded according to the hypothesis of gradually abandoned and filled valleys, the longitudinal profile should show no abrupt breaks in slope. In the headward portions of the valleys, where almost all surface waters escape through subterranean solution channels or flow through the valley fill, slope-wash fans and limestone sinks would destroy the original continuous down-valley gradient and would produce, instead, a profile which would be locally reversed or undulating. Traced down-valley to progressively lower elevations, the effects of solution would gradually diminish, and a decreasing percentage of surface water would be lost to subterranean flow. At a sufficiently low elevation the channel of a wet-weather surface stream would appear, while at still lower levels the surface stream would gain sufficient competence to sweep the valley floor clear of debris. Still farther down-valley the stream would begin actively to corrade its channel.

Under the hypothesis of mature valleys, an abrupt change of gradient or knickpoint, or a series of such features, should be found to separate the upper mature valleys from the lower youthful valleys. Immediately below the knickpoints a transverse profile of the valley should show a narrow, steep-walled canyon incised into a broad, open upper valley. Furthermore, the present position of the breaks in longitudinal profiles should be related to the distance from the Colorado River. Thus, on the southern part of the Kaibab Plateau, where drainage on the flanks of the arch has but a short distance to go to the master-stream, the rejuvenation should have advanced farthest toward the plateau summit. Farther north on the Kai-

bab, where drainage must follow a long course across the Marble or Kanab platforms to reach the Colorado, the point of change in longitudinal stream profiles should occur much lower on the flanks of the Kaibab arch.

Field study reveals complete accordance of the facts with deductions made from the hypothesis of abandoned valleys resulting from limestone solution, and also the absence of expected consequences of the hypothesis of mature valleys. Traced downstream from their heads, valleys show gradual transition from the undulating-floored types of the Douglas fir zone on the high Kaibab, through the flat-floored forms of the western yellow pine zone, to the young valleys and canyons of the pinyon-juniper and lower zones. Moreover, the change of form occurs everywhere at about the same altitude, rather than varying with distance to the master-stream.

The possible existence in Jacob Canyon of a narrow young valley incised into a broad upper valley of an older cycle has been described by Johnson[33] at the place where the canyon emerges from the West Kaibab fault-line scarp (Fig. 1). He also considered the possibility that a harder layer of rock, which coincides with the floor of the broad upper valley, may be responsible for the conditions; but, because the narrow lower canyon is cut far to one side of the center of the upper valley, he concluded that the compound valley profile is valid evidence of two cycles of erosion.

The mouths of Jacob Canyon and of other similar canyons emerging from the same scarp farther south were examined by the present writer. The same resistant beds referred to by Johnson consistently form structural terraces in the walls of all these canyons, none of which can therefore be considered to exhibit features of cyclic significance. The asymmetry of Jacob Canyon, as seen from the base of the scarp, is explained by a sharp bend which the stream makes just before emerging from the scarp. Contrasting slip-off and undercut slopes produce the asymmetrical profile. The other canyons appeared to be generally symmetrical in cross section where they leave the scarp. Structural terraces are a conspicuous feature of valley walls throughout the Grand Canyon region, and nowhere has the writer observed any compound transverse profile which could not be readily thus explained.

*Absence of surface streams.*—Under the hypothesis of abandoned valleys surface-stream channels should be absent or very short, whereas under the hypothesis of mature valleys normal surface-stream channels should be present. In a passage quoted earlier Dutton has emphasized that surface streams are conspicuously lacking in the Kaibab valleys.[34] Locally there are tiny streams which flow short distances before terminating in sinks, but these are relatively insignificant. In many places a search of the valley from side to side revealed no trace of a channel. Exceptions to the rule are a few young gullies, 2–12 feet deep, sharply trenched into the valley fill. They seem to be temporary forms, in some cases initiated by man-made excavations. One such gully in Coconino Wash (Fig. 1), 2 miles east of Highway 64, has resulted from digging of a trench. Another, in Jacob Canyon (Fig. 10), seems to have been initiated by excavation of valley fill for highway construction. In general, surface-stream channels

[33] Pp. 147–48 of ftn. 14 (1909).

[34] Dutton, ftn. 8 (1882).

are commoner and longer in valleys of the western yellow pine zone than on the higher parts of the Kaibab.

As further proof of the absence of surface channels, the countless slope-wash fans may be cited (Fig. 11). On the fans themselves channels are usually absent, indicating that the fans are being built by gradual accumulation of slope wash, without disturbance of the grass cover and without the concentration of water into braided streams usually found on alluvial fans being rapidly constructed. Were the open forms of the valleys produced solely by the attainment of maturity in an earlier cycle, the valleys should be constantly swept clean of such debris by streams, especially in such a humid region as the higher Kaibab Plateau.

FIG. 10.—Jacob Canyon, 2½ miles north of Jacob Lake. Valley fill trenched to a depth of 10 feet by a recent gully.

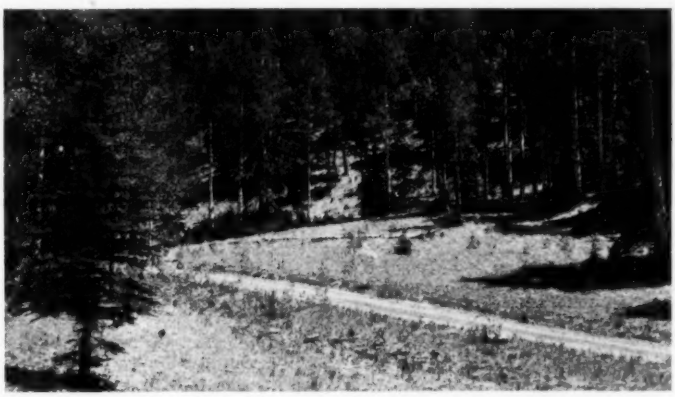


FIG. 11.—A slope-wash fan built out across Kanabownits Canyon on the Kaibab Plateau

*Character of the valley fill.*—Nature of the material in valley bottoms is extremely important in determining the origin of valleys on the Kaibab and Co-

conino plateaus. Under the hypothesis which explains the open valleys as mature forms produced at the end of a prolonged cycle of denudation, it may be supposed that the stream system was nicely adjusted with respect to the load of debris supplied to it from the valley walls and that alluvium in the valley floor consisted principally of fluviatile sands, silts, and gravels.

Davis[35] does not seem to have regarded regional uplift, accompanied by intrenchment of the lower stream courses in a new cycle, as having been instrumental in producing any notable change in balance of load and volume in the upper stream courses, for he makes no mention of this possibility. That such an assumption may be precarious is apparent from the great changes in amount of precipitation which attend changes of altitude. An increase of elevation of the region as a whole to the extent of 1,500–2,000 feet following peneplanation might have increased the precipitation by two to three times, on the basis of present-day climate zones. Furthermore, the increase in relative height of the Kaibab arch as weak rocks were stripped from adjacent lower platforms might have greatly increased precipitation resulting from forced ascent of air passing from west to east across the region. It would thus seem that uplift in the Canyon cycle would have caused streams on the higher parts of the plateau to increase greatly in volume, thereby permitting them to sweep all debris from their channels and to incise the rock toward a new profile of equilibrium. Rejuvenation of the streams in their upper parts, rather than maintenance of their former condition, would seem to be the logical result of the history postulated by Davis. Nevertheless, for the purposes of further analysis of the two hypotheses, let us assume, as Davis, Johnson, and Robinson seem to have done, that the mature valleys have changed little since their uplift at the close of the Plateau cycle. The alluvium found in them should consist largely of well-sorted and clearly stratified silts, sands, or gravels with well-rounded pebbles.

Under the hypothesis of abandoned valleys, one would expect to find thick deposits choking the valleys. The lower part might consist largely of fluviatile material representing the aggradation by streams robbed of their tributaries and broken into small units by diversion of water to underground channels. The fluviatile materials should grade upward into more poorly stratified materials, then into pure slope wash or sheet wash, revealing only the faintest evidence of sorting and a rude stratification or none at all.

To determine the character of material in valleys of the Kaibab and Coconino plateaus, it was necessary to examine artificial excavations and the narrow gullies already described. Although these places usually permitted only the upper 2–4 feet of fill to be studied, it was found invariably to consist of unsorted and very poorly stratified or of unstratified slope wash. The material is a dark-brown sandy loam containing remains of plant roots to as great a depth as could be observed. Abundant irregular chert fragments, relatively insoluble, make up a large proportion of the fill. A particularly deep gully in the floor of Jacob Canyon (Fig. 10) afforded opportunity to study a 10-foot section of the fill. The upper 4 feet is a black soil with some Kaibab chert fragments. Below this the material consists largely of small irregular chert fragments, rudely stratified but entirely lacking in rounding and

[35] Ftn. 11 (1901).

sorting characteristic of stream deposits. The fill in the upper 4 feet of the gully wall in Jacob Canyon is strikingly similar to that observed in a gully 3 feet deep in Coconino Wash, on the Coconino Plateau (Fig. 1). It can be said with assurance that the upper few feet, at least, of the fill in open valleys of the Kaibab and Coconino plateaus consists of locally derived slope wash, a condition which would be expected where surface streams ceased to flow in a system of youthful valleys.

*Steepness of valley walls.*—There may arise in the reader's mind a question as to whether the topographic forms characteristic of extensive limestone solution in a humid climate could not have been superimposed upon a system of truly mature valleys developed in an earlier cycle of erosion. Although the characteristics of the earlier event would by now have been obliterated by the more recent changes, is it not possible for the two processes affecting valley development each in turn to have been active? A satisfactory answer probably cannot now be given on the basis of known facts, but there is one method of approach which does offer hope of a solution to the problem. If the valleys had reached maturity in a former cycle, the slopes of their walls should consistently be more gentle than for young valleys at lower elevations. After abandonment by surface streams these slopes would weather to even lower angles. If, however, the valleys were young when abandoned as a result of limestone solution, they might still maintain in places the relatively steep walls, particularly in the western yellow pine zone, where valleys were more recently abandoned and where solution processes are only moderately active.

Steepness of valley walls has already been cited as a characteristic of western yellow pine zone valleys. Portions of the valley of Coconino Wash (Fig. 8) were unquestionably young and steep-walled when deserted by surface drainage. Maximum angles of slope measured on young valleys on the lower flanks of the Kaibab and Coconino plateaus and on the Marble Platform range from 20° to 32°. Those of Coconino Wash, where measured, are from 20° to 25°. For long stretches Kanabownits Canyon in the Douglas fir zone of the Kaibab Plateau (Fig. 2) has maximum slopes of 25° to 30°. These figures seem to indicate that the higher valleys were all young, not mature, when abandoned by surface drainage and resembled in most respects the young valleys now found at lower elevations. The possibility of a compromise is thus excluded. Instead, a further unexpected and unexplained difficulty in accepting Davis' hypothesis of mature valleys is revealed.

*Summary of deductive analysis.*—All the consequences deduced from the hypothesis of abandoned valleys resulting from limestone solution were found to agree with the facts gathered in the field and from topographic maps. Sinkholes, karstlike park floors, and springs issuing from the plateau margins are expected features of extensive limestone solution and are abundant on the Kaibab Plateau. Although such forms could also occur under Davis' hypothesis of mature valleys, their presence would be only incidental. The form of valleys on the Kaibab and Coconino plateaus is closely related to character of the climate. This correlation is to be expected if valley form depends on degree of underground drainage development. Although a general correspondence of open valleys with high elevations is likewise an expected consequence of the hypothesis of mature

valleys, the extremely close correlation of valley form and climatic zone, requiring a threefold classification of the valleys, seems too precise to be explained solely by the two-cycle erosion history which Davis proposed. Traced downstream from their heads, the valleys change very gradually in form, even as the climatic and vegetation zone schange, whereas under the hypothesis of mature valleys a break in profile, or a series of breaks, should mark the change from maturity to youth. Moreover, a composite transverse valley profile, independent of structure, should be recognizable under Davis' explanation; but none was found. Thick slope wash chokes the valleys, an expected result of the disappearance of surface streams; but sorted, rounded, and stratified stream deposits, the expectable product of mature streams, were not seen. Finally, the steepness of valley walls in all zones indicates that the valleys were young when abandoned, rather than mature, as Davis postulated. It is therefore concluded that the hypothesis of valley abandonment resulting from limestone solution logically explains observed facts, whereas Davis' hypothesis of mature valleys fails to account for many of them.

## PARKS OF THE KAIBAB PLATEAU

### DESCRIPTION OF PARKS

The parks of the Kaibab Plateau are broad, open depressions having interior drainage systems and numerous sinkholes in their floors. They lie in the Douglas fir zone,[36] above 8,000 feet elevation. Although the parks themselves are entirely free from trees, they are surrounded by a dense forest of fir, pine, and spruce, ending along a sharp line (Fig. 12). Quaking aspen frequently form patches or belts at the forest margin, standing between the open ground and the massed evergreens. The park floors bear grasses and wild flowers. The unique distribution of vegetation is largely responsible for the striking appearance of the parks.

The principal parks are highly elongate and form a connecting series of linear depressions about 14 miles in total length along the summit of the Kaibab arch (Fig. 1). They are, from north to south, Pleasant Valley Park, Demotte Park, and Little Park. They are 250–400 feet deep. From the summit heights bordering the parks on either side the land surface slopes away from the parks, thus forming two north-south trending ridges which are broad and asymmetrical, their steeper sides facing into the parks. Inasmuch as the strata dip both east and west from the line along which the parks lie, the ensemble may be described as a breached anticline. Other parks, much smaller than the axial chain, are distributed over the plateau. One of the largest of these is Dry Park, 6 miles west of Demotte Park (Fig. 1). Another is in the vicinity of Three Lakes (Fig. 13). All tend to be elongated in a north-south direction.

Pleasant Valley Park, northernmost of the axial series, is about 3 miles long and 1 mile wide. It is distinguished from the parks farther south by its extremely irregular karstlike floor, composed of limestone masses and intervening sinks. These features have already been described in a previous section dealing with the evidences of extensive solution. Although drainage is largely interior, the park wall on the east side is notched by deep water gaps cut to the level of the park floor and providing exterior drainage for very limited areas of the park. Similar gaps are present along the eastern walls of parks farther south. As is generally true throughout the system of

[36] Pearson, pp. 9–12 of ftn. 29 (1931).

FIG. 12.—Demotte Park, largest of the axial Kaibab parks. View is southward and shows in center distance Kaibab Lodge, located at a constriction in park. Grand Canyon Highway at left.

FIG. 13.—Large, shallow sinkhole in a small park at Three Lakes on the Kaibab Plateau

Kaibab valleys, surface streams in these gaps play only an insignificant role in draining the plateau.

Demotte Park is about 8 miles long and 1–2 miles wide. One-third of the distance from its north end is a narrow constriction, at Kaibab Lodge, dividing it into two unequal basins (Fig. 12). Dutton[37] has described the southern end of Demotte Park in the following sentences:

> It is a depressed area in the heart of the plateau and is on every side girt about by more elevated ground rising by strong slopes 300 or 400 feet above its floor. The borders and heights above are densely forest-clad, but not a tree stands within the park itself. . . . . On either hand is the forest, covering the slopes and the heights above, but ending suddenly at the foot of every incline. Before us to the southward stretches the open field with hardly an undulation. Six or seven miles away we can see the sylvan walls approach each other, leaving a narrow gateway between the tall spruces where the surface of the ground for a moment is sharply projected against the sky. The scene is, on the whole, a very attractive one. . . . . The only alleviating contrast is between the smooth expanse of the park and the myriads of sharp spikes which terminate the tree tops.

Perhaps the most important difference between Demotte and Pleasant Valley parks is that the former lacks the rough karstlike topography of Pleasant Valley Park and is, instead, relatively smooth surfaced. Contrary to Dutton's statement that there is hardly an undulation, the floor of Demotte Park is gently rolling (Fig. 12), because broad, shallow fans have been built out across the park from both sides. Thus the park floor is largely a constructional surface. Sinkholes and limestone outcrops are far less abundant than in Pleasant Valley Park. South of Demotte Park, and connected to it by the "Sylvan Gate,"[38] is Little Park, about 2 miles long (Fig. 1).

Along the summit of the Kaibab arch north of Jacob Lake is Summit Valley (Fig. 1), another elongate depression. It differs from the parks farther south in that it has surface drainage out through the open north end. Moreover, it is in the pinyon-juniper zone, characterized by a semiarid climate, surface streams, and relatively meager limestone solution. Together with sparse woodland and sage growth and abundant rock outcrops, these factors give Summit Valley a totally different aspect from the higher axial parks farther south.

### HYPOTHESES OF ORIGIN OF THE PARKS

*Hypothesis of faulting.*—The possibility that parks of the Kaibab Plateau are primarily grabens, only slightly modified by erosion, is worthy of careful consideration—especially because many grabens occur near the southern end of the East Kaibab monocline, in the Cameron-Wupatki region, while local faults are present near the monocline along the east flank of the Kaibab Plateau.[39] Dutton reports that Powell and Gilbert suspected a long, narrow wedge on the plateau summit had been dropped between two faults;[40] but, as noted earlier, the writer has failed to find the original statements.

Direct evidence of faulting, other than the linear nature of the string of parks, was not found. The park walls are irregular in plan, with spurs projecting out into the park or shallow recesses indenting the walls. The rectilinear base line, characteristic of fault and fault-line scarps, is not present. In all the grabens and single faults studied by the writer in the vicinity of the East Kaibab monocline the rectilinear form of the scarps,

[37] Pp. 135–37 of ftn. 6 (1882).

[38] *Ibid.*, p. 138.

[39] Babenroth and Strahler, ftn. 1.

[40] Dutton, p. 193 of ftn. 6 (1882).

even where thoroughly dissected, is a striking characteristic. Dutton found the Coconino sandstone outcropping in the floor of a small park (Thompson Canyon?) a few miles south of Little Park but along the same axial line. Because the Coconino sandstone was in the correct stratigraphic position with regard to the series exposed in the adjacent valley walls, he concluded that the parks could not be the result of graben faulting.[41]

It has already been noted that in the floor of Pleasant Valley Park patches of limestone were found, at least one of which seems to have been in some manner lowered more than 250 feet with relation to the stratigraphic column in the park walls (Fig. 4). While this might appear to be the result of graben faulting, the small size of the limestone masses and their various inclinations would seem to require an unusually intricate pattern of intersecting faults.

Thus the hypothesis of faulting seems inadequate to explain the parks. There is, however, a reasonable possibility that faulting on a small scale produced zones of weakness which were greatly enlarged and deepened by running water and limestone solution.

*Hypothesis of a disrupted antecedent stream.*—Dutton supposed that the axial parks mark the former site of an important south-flowing Miocene tributary to the Colorado River. He cited two causes for its destruction: the arid climate of the Pliocene and upwarping of the Kaibab Plateau, reversing the stream's gradient.[42]

Davis has pointed out the difficulties attending Dutton's explanation.[43] The close association of the chain of parks, including Summit Valley, with the exact crest of the Kaibab arch seemed, to Davis, highly improbable on the basis of chance. Moreover, with independent evidence that the deformation which produced the Kaibab fold is relatively ancient and preceded the stripping of the Mesozoic cover, it is impossible for the string of parks ever to have possessed a continuous slope southward from the northernmost part of the arch.

*Hypothesis of longitudinal subsequent streams.*—To replace Dutton's inadequate hypothesis of an antecedent stream valley, Davis outlined a new history of erosion of the Kaibab Plateau, which refers back to the time when the heavy Jurassic sandstones still roofed the Kaibab arch. A chain of anticlinal valleys was formed by the breaching of the crest by streams which had cut through the massive sandstones and were sapping the weak Triassic shales beneath them. The longitudinal subsequent streams eventually cut through the shales and became entrenched in the Kaibab limestone. As the Jurassic and Triassic strata then retreated down the flanks of the Kaibab anticline, the longitudinal summit streams, which had at first derived much of their volume from obsequents flowing down the in-facing Jurassic cliffs, became greatly reduced in size and cutting power—the state in which they are found today.

The hypothesis of longitudinal subsequent streams appears to be free of serious difficulties and at the same time is based upon a type of stream development long understood in the denudation of anticlines.

Although Davis' hypothesis provides a reasonable explanation of the general position and form of the Kaibab parks, it is not in itself adequate to explain the

[41] *Ibid.*, pp. 171, 193.

[42] *Ibid.*, pp. 192–95.

[43] Davis, pp. 155–58 of ftn. 11 (1901).

finer details of topography, such as the interior drainage of much of the area of the parks, the abundant sinks, and the broad fans of waste. In order to complete the explanation and to bring it into accord with the new hypothesis proposed for the open Kaibab and Coconino valleys, it must be added that solution of the limestone and diversion of drainage to underground channels largely destroyed the shrunken stream system which cut the axial park valleys. The extent to which the parks have been deepened and widened since their abandonment by surface streams cannot be determined, but the floors may have been lowered as much as 100 or 200 feet. Davis' failure to describe and account for the features of limestone solution may be explained by the fact that his route of travel carried him north of the principal parks, through an area where solution features are not conspicuous.

Other smaller parks on the western slopes of the Kaibab Plateau also trend north-south and may have originated by the entrenchment of subsequent streams along the base of the retreating Jurassic escarpment or as later subsequents on a system of fractures in the limestone. Further detailed field study will be required to clarify this question. Abandonment of surface drainage and modification of topography by limestone solution would have then produced typical parks, similar to, but generally much smaller than, those of the principal axial chain.

## SUMMARY AND CONCLUSIONS

Valleys of the Kaibab and Coconino plateaus fall into three distinctive types, each of which is closely related to a zone of climate and vegetation determined primarily by altitude. On the lower flanks of the plateaus and on the Kanab Plateau and Marble Platform are youthful canyons being actively cut by wet-weather streams. They lie in the semiarid pinyon-juniper and lower zones, below 7,000 feet elevation, where evidences of limestone solution are meager. In the western yellow pine zone, 7,000–8,000 feet, valleys are steep-walled, flat-floored, and lack surface-stream channels. Fans of slope wash frequently are built out across the valleys. Valley-bottom fill also consists of slope wash. In the Douglas fir zone, above 8,000 feet on the Kaibab Plateau, a cool, humid climate supports dense forests of fir, spruce, pine, and aspen. Valley walls and floors are thickly mantled by waste, and outcrops are largely concealed. Fans of slope wash block the valley floors, while abundant sinkholes occupy both the valley floors and interstream areas. Significant surface streams are absent.

All observed facts seem to be explained fully by a hypothesis of valley abandonment due to the increasing effects of limestone solution at higher elevations. Valleys initially carved by vigorous, youthful streams were deserted as underground drainage developed. Valleys fell into decay, accumulating a mantle of slope wash, and were eaten into by sinks. At progressively lower and drier elevations these effects disappear, and in the semiarid pinyon-juniper zone surface streams continue to incise the valleys.

The hypothesis of mature valleys, proposed by W. M. Davis and supported by Douglas Johnson and H. H. Robinson, explains the contrast in valley forms at higher and lower elevations as the result of two erosion cycles. This hypothesis has been shown to be unsatisfactory in several respects. It does not explain the threefold classification of valleys or their close coincidence with climatic and vegetation zones. Moreover,

the abundant features of limestone solution and many detailed characteristics of the valleys themselves are not accounted for in the older hypothesis.

The principal parks of the Kaibab Plateau lie in a chain trending north-south and coinciding closely with the structural crest of the Kaibab arch. They may have originated as valleys of longitudinal subsequent streams formed while the Kaibab arch was being stripped of its Mesozoic cover or as subsequent streams along a series of minor fault lines. Through the development of underground drainage the surface streams were diverted and their valleys enlarged and deepened into solution basins.

If the hypothesis of valley abandonment due to limestone solution is accepted in favor of the hypothesis of mature valleys, one of the major lines of evidence for the Plateau cycle of erosion, closing in the development of a widespread peneplane, must be discarded. The results of the present study are, therefore, of critical significance in the geomorphic history of the entire Grand Canyon district.

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# THE ANTECEDENT-PLATFORM THEORY

J. E. HOFFMEISTER
University of Rochester, Rochester, New York

H. S. LADD
U.S. Geological Survey, Rolla, Missouri

ABSTRACT

The Antecedent-Platform theory for the origin of coral reefs holds that any bench or bank that is located at a proper depth within the circumequatorial coral-reef zone is potentially a coral-reef foundation. If ecological conditions permit, a reef may grow to the surface from such a foundation without any change in sea-level. Reef foundations, or platforms, are formed by erosion, deposition, volcanic eruption, or earth movement or by combinations of two or more of these processes. Examples of each type from Fiji and Tonga are cited, some of the examples being visible beneath elevated reefs, others inferred beneath existing reefs.

In Fiji and in parts, if not all, of Tonga, pyroclastic action has been the dominant form of volcanic activity since early Tertiary time; and many coral reefs probably developed on platforms cut by the waves in unconsolidated material of this kind. Platforms originating below the depth limit of reef corals were veneered with tuffaceous limestone and built to the zone of reef-coral growth by organisms other than corals, chiefly Foraminifera and algae.

## INTRODUCTION

The origin of coral reefs, particularly barrier reefs and atolls, still provokes discussion after more than one hundred years. The isolation of many flourishing coral-reef areas, the difficulties involved in examining more than the surface of a living reef, and the fact that most investigators have devoted only a very brief time to field work in any one locality—all have added to the complexities of the problem.

In two earlier discussions we have critically reviewed outstanding theories for the origin of coral reefs: the Subsidence theory[1] and the Glacial-Control theory.[2] In the last-named paper we briefly outlined the Antecedent-Platform theory as developed by various workers and stated our intention of publishing the present, more comprehensive, account of the theory—an account based in large part on our field studies in Fiji and Tonga. We wish to express our thanks to Drs. T. Wayland Vaughan and R. T. Chamberlin, both of whom have read and criticized the present paper.

## CLASSIFICATION OF CORAL-REEF THEORIES

The many coral-reef theories that have been proposed may be divided into two main groups: (1) those which require a change of sea-level relative to the reef foundation and (2) those which hold that reefs may develop without a change in sea-level relative to the reef foundation. Some of the more important theories of the first group are:

*a*) Darwin's theory of a sinking land area and consequent rising sea-level. Under these conditions, it is stated, the corals grow upward and outward, converting fringing reefs into barriers and finally into atolls. Dana and Davis strongly supported this theory.

*b*) The Glacial-Control theory ably developed by Daly. It postulates a rising sea-level due to the return of water to the sea following periods of glaciation.

[1] J. E. Hoffmeister and H. S. Ladd, "The Foundations of Atolls: A Discussion," *Jour. Geol.*, Vol. XLIII (1935), pp. 653–65.

[2] Ladd and Hoffmeister, "A Criticism of the Glacial-Control Theory," *Jour. Geol.*, Vol. XLIV (1936), pp. 74–92.

c) Vaughan's theory of pre-existing flats formed by various processes, followed by gradual submergence caused by crustal movements or rising ocean-level.

d) Semper's theory of reef formation on a rising submarine volcanic mound.

The second group of theories includes:

a) The Rein theory of the accumulation of organic deposits on still-standing submarine summits to serve as foundations for atolls.

b) The Murray theory, which extends the Rein theory, stating that atoll lagoons are enlarged by solution as the reef grows outward on its own talus material.

c) Agassiz's theory for the formation of atolls by solution operating on existing limestone masses and the formation of barrier reefs by growth of corals on platforms made by marine erosion without change of sea-level.

d) The theory of Wharton, later expounded by Gardiner, that corals grow upon foundations made by submarine planation of volcanic islands.

e) The Antecedent-Platform theory as here presented; as noted below, many workers have given support to this concept.

## THE ANTECEDENT-PLATFORM THEORY DEFINED

The Antecedent-Platform theory holds that any bench or bank—even one not "smooth"—that is located at a proper depth within the circumequatorial coral-reef zone can be considered a potential coral-reef foundation and that, if ecological conditions permit, a reef could grow up to the surface without any change in ocean-level. This is a general principle that applies to coral reefs of all ages—preglacial, glacial, and postglacial.

Many who have studied coral reefs have thought it necessary to postulate a pre-existing platform. The first coral-reef theory of this type appeared in 1821, when Tyerman and Bennet stated that the steep coastal cliffs of Tahiti indicated that the barrier reefs of this island were formed on the outer edges of wave-cut platforms. Andrews, Chamberlin, Daly, Gardiner, Guppy, Setchell, Vaughan, Wharton, and many others have given support to the idea that reefs have developed on antecedent shelves.

Many of those who postulate an antecedent platform seem to feel that a second requirement—a rising sea-level—is also necessary. The rise in sea-level may be due to an actual rise in ocean-level or to a sinking of the land. It is our belief that such a sea-level change may stimulate reef growth, but we hold that it is not *essential* for the formation of a flourishing barrier or atoll.

## FORMATION OF THE PLATFORM

### DEFINITION

The term "platform" is here used in a broad sense to include all foundations upon which reef organisms may establish themselves. The surfaces of these platforms may be flat or inclined, smooth or somewhat irregular. In general, subhorizontal foundations are more favorable for reef growth than other types, and it is probable that most reef foundations are fairly flat. Under certain conditions, however, other foundations may serve, and they are therefore included under the term "platform."

As T. W. Vaughan[3] has pointed out, platforms may originate in any one of a number of ways. The chief methods are included in the outline below. Obviously, there is a certain amount of unavoidable duplication in a classification of this sort, for most platforms are the result of the operations of at least two agents. Thus, a submarine platform built of pyroclastics might be classed as a platform of deposition or as one due primarily to volcanic activity.

[3] "Fossil Corals from Central America, Cuba, and Porto Rico, with an Account of the American Tertiary, Pleistocene, and Recent Coral Reefs," *Bull. U.S. Nat. Mus.*, Vol. CIII (1919), p. 324.

CLASSIFICATION

I. Platforms of erosion
   1. Submerged coastal lands
   2. Wave-cut platforms
II. Platforms of deposition
   1. Pyroclastics
   2. Limestones
   3. Fluvial sediments
III. Platforms made by volcanic eruption
   1. Crater rims
   2. Pyroclastic banks
IV. Platforms made by earth movements
   1. Submergence of land
      *a*) By downwarping
      *b*) By faulting
   2. Uplift of ocean floor

## EXAMPLES OF PLATFORMS VISIBLE BENEATH ELEVATED REEFS OR INFERRED BENEATH EXISTING REEFS

### PLATFORMS OF EROSION

*Submerged coastal lands.*—Coastal lands which long have been subjected to subaerial erosion and later submerged make excellent platforms on which reefs, particularly of the barrier type, may form. Examples of reef platforms that appear to have been made in this manner are found off the north-central and northeast coasts of the large island of Vitilevu in Fiji. Field data obtained by Ladd, who examined the coasts and the reefs in 1926 and 1928,[4] lend support to the generalized conclusions of Vaughan, whose interpretations of Fijian reefs were based largely on a study of hydrographic charts.[5]

The north-central coast is a strip of dissected plain extending eastward from near Vatia Point to the headlands on the north shore of Vitilevu Bay.[6] It represents a down-faulted block, 30 miles in length, lying between the sea and the eroded Nandarivatu fault scarp that rises more than 2,000 feet above the sea. The strip averages 5 miles in width. The rolling hills on its surface are higher near the scarp than near the sea; but some of them reach the shore, and others extend into the sea to form low headlands or conical islands.

Viewed as a whole, the coast is irregular, indicating submergence; but a narrow, discontinuous strip of flat coastal plain suggests a small recent emergence. The coast is bordered by a submarine platform, 5–8 miles in width, that appears to be a submarine continuation of the late-mature topography of the land. A broad barrier reef fringes the edge of the submarine platform; reef patches and a shore platform are also present.[7]

The northeast coast of Vitilevu, which adjoins the above-described strip, extends from the headlands south of Vitilevu Bay southeastward for 20 miles to Tanavuso Point and is deeply embayed. In this strip of dissected coastal plain, averaging 5 miles in width, deep bays alternate with bold promontories. Many of the promontories dip steeply to the sea, and in some places rocky stacks are present offshore.

This embayed coast is bordered by a well-developed submarine platform, 5 miles in width, that is spotted with reef patches but unrimmed by a barrier reef. In referring to this general area Vaughan expresses the opinion that the absence of a marginal reef shows clearly that reefs, where present, are superposed on an antecedent platform; he contends that the suggestion made by W. M.

[4] "Geology of Vitilevu, Fiji," *Bernice P. Bishop Mus. Bull. 119* (1934).

[5] "Sketch of the Geologic History of the Florida Coral Reef Tract and Comparison with Other Coral Reef Areas," *Jour. Wash. Acad. Sci.*, Vol. IV (1914) pp. 26–34; pp. 189–524 of ftn. 3 (1919); "Coral Reefs and Submerged Platforms," *Proc. Pan-Pacific Sci. Cong., Australia*, Vol. II (1923), pp. 1128–34.

[6] Ladd, sketch map, fig. 2, p. 9 of ftn. 4 (1934).

[7] *Ibid.*, sketch map, fig. 9, p. 69.

Davis, that the entire platform is due to infilling behind a reef which in places has ceased to grow, was farfetched.[8]

The above-described northeast coast terminates abruptly on the south, where at Tanavuso Point it abuts against the undissected coastal plain of the Rewa physiographic province. From Tanavuso Point to the mouth of the Rewa the coast is low and of the emerged type. The reef platform broadens beyond Tanavuso Point as it swings eastward to encircle the island of Ovalau,[9] but it remains unrimmed by a barrier until a point northeast of Ovalau is reached.

*Wave-cut platforms.*—Marine erosion has done much to modify the shapes of islands; and in some instances, as will be shown, it has been primarily responsible for the formation of platforms that have served as foundations for coral reefs. Before citing specific examples, however, it seems desirable to consider the nature of marine erosion under the somewhat unusual conditions that obtain in the Southwest Pacific.

The islands of Fiji and Tonga are in an area where the southeast trade winds and the waves engendered by them prevail for nine months out of each year. Under these conditions it is not surprising to find that, in most cases, the windward sides of islands differ from the leeward sides. The dominance of the southeast trades simplifies the task of recognizing land forms due primarily to marine erosion. Thus, marine erosion is partly responsible for the steep windward slopes and terraced profiles that characterize many of the islands of Fiji and Tonga. Other types of evidence indicative of its operation in Lau (eastern Fiji) are given below.

1. Distribution of limestone relative to volcanic rock. In Lau, in the islands of Vanua Mbalavu, Thikombia-i-Lau, Malatta, Katafanga, Oneata, Lakemba, and Komo, the main mass of the limestone that veneers the volcanic core lies to leeward. This suggests that marine erosion has stripped off the limestone cover from the windward side. No striking exceptions to the rule are yet known in Lau.

2. Distribution of the highest land. On the basin-shaped islands of Fulanga and Tuvuthá and on Lakemba there are high, even-crested, more or less castle-shaped masses that lie close to the leeward (northwest) coast. These elevations appear to be remnants of high rims that once encircled the islands. No remnants of this kind were found on the windward sides of any of the numerous islands that we visited in Fiji and Tonga.

3. Distribution of remnants of younger Tertiary limestone. In Lau we recognized three exposures of a richly fossiliferous Tertiary limestone that is younger than a more widespread limestone that blankets the volcanic cores of most of the islands. Two of the three exposures recognized lie near sea-level on the leeward sides of their respective islands—Vanua Mbalavu and Tuvuthá. The third, at an altitude of 120 feet, is an isolated remnant surrounded by volcanic rocks in the middle of the eastern end of Susui. The presence of the younger limestone exclusively on the leeward side of the islands is an indication of the greater cutting power of marine erosion on the windward side.

All the islands that we studied in Lau are surrounded by a reef platform of some sort. The platforms around the Exploring Isles, Katafanga, Lake aba, Namuka, and Mothe-Karoni, are appreciably wider to windward than they are to leeward. This condition also obtains

[8] Vaughan, p. 310 of ftn. 3 (1919).

[9] Ladd, ftn. 4 (1934).

for Tuvuthá and Naiau, but the discrepancy on these two islands is not striking. On Mango, Thithia, Fulanga, Yangasá, Kambara, Wangava, and Vanua Vatu the leeward platform is approximately the same width as that to windward. On Komo, Ongea, Oneata, and Aiwa the leeward platform is distinctly wider than the platform to windward. In the case of Komo, this condition is probably due to faulting; for Ongea, an explanation involving reef protection can be suggested; but for Oneata and Aiwa, no entirely satisfactory explanation is offered, though it is possible that original differences in the configuration and elevation of the volcanic foundation may be at least partly responsible.

There is no doubt that ocean-levels were lowered during the glacial stages of the Pleistocene. We believe that under these conditions normal valleys on volcanic islands were widened and deepened and that on limestone areas solution by ground water was carried to greater depths than formerly possible. The work of waves was likewise stimulated during the glacial stages, for with lowered sea-level they could erode levels that previously lay beneath their zone of attack. It is believed, for example, that large parts of the lagoon floor, which now forms a broad platform around most of Ongea, were cut during the Pleistocene; but it is difficult to evaluate the importance of the work of the waves exactly. The existing barrier of Ongea stands on the seaward edge of this platform.

It is believed, however, that it is not necessary to call on low-level Pleistocene erosion to explain all now-submerged wave-cut platforms. In fact, it is very evident that wave action at the present level is capable of reducing certain islands either partially or entirely to submarine platforms. This was pointed out long ago by Wharton and later developed by Gardiner. The effectiveness of this action is largely dependent on the character of the material composing the island. If the material is unconsolidated volcanic ash and scoria, the action is rapid.

In 1928, on a visit to Falcon Island, an active pyroclastic cone in Tonga, we gained an idea of the speed and the general effectiveness of normal wave action on a pyroclastic mound.[10] The conditions seen there are described below because we consider them typical of the early stages of platform building in the Southwest Pacific.

Falcon has erupted several times since its discovery in 1865. At the time of our visit it was a low, gently sloping conical island, 2 miles in diameter, rising to a height of 365 feet. The crater, which lay to windward, had been breached by the waves. High cliffs had been cut to windward on both sides of the breached crater, much of the material thus removed by wave action having been shifted to leeward, where an extensive shoal had been built. The sides of the conical island and the inner walls of the crater were trenched by deep gullies. The island was composed entirely of unconsolidated pyroclastic material—a mixture of tuff, scoria, pumice, and blocks of solid lava up to 3 feet in diameter. The striking feature was not the way in which the heap of cinders was piled above sea-level but the rapidity with which the waves were reducing it to a shoal. Since the island lay in the open sea and lacked protecting reefs, even the broad, low surges engendered by the normal trade

[10] J. Edward Hoffmeister, Harry S. Ladd, and Harold L. Alling, "Falcon Island," *Amer. Jour. Sci.*, Vol. XVIII (5th ser., 1929), pp. 461–71.

winds were effectively eroding it. Sailing close to shore on a calm day, we saw huge sections of the undercut cliffs sliding bodily into the sea. The surf everywhere was black with scoria, many of the pieces being fairly well rounded. We estimated that 12,000,000,000 cubic feet of material still lay above sea-level and that the sea had removed 18 mile-feet from the island to form the adjacent shallows. During this same interval of time, it was estimated, fluvial agencies had removed only $\frac{1}{10}$ mile-feet.

Periodically erupting Falcon has been reduced to a shoal on more than one occasion. Its history demonstrates clearly that isolated pyroclastic islands may be quickly leveled, largely by normal wave action. We believe that many of the minute isolated islands and reefs that occur in the Southwest Pacific have a core that is similar in all essential features to that of Falcon. In the vast majority of cases it would seem that the pyroclastic mounds resulting from the eruptions of normal-sized vents are not built into stable islands by volcanic action alone. They are fated to become shoals periodically during the life of the volcano and for the last time after volcanic action ceases. It is at this final stage that other processes are inaugurated which build a more permanent island.

The depth below sea-level to which wave action can reduce a mound of this type has long been a subject of speculation. Geikie, Wharton, and Gardiner believed a flat bank, 30–50 fathoms deep, might be produced in this manner unless the mound became protected at a lesser depth by the growth of coral-reef organisms. It is known that Falcon Island had become reduced to a bank between 5 and 10 fathoms deep between the time of its eruption in 1883 and the next volcanic phase in 1912. Long ago, W. J. L. Wharton[11] pointed out that Sabrina Island in the Azores, formed in 1811 by pyroclastics, was soon washed away to a depth of 15 fathoms. There seems to be no doubt that wave action can reduce pyroclastic mounds to at least 30 fathoms below sea-level. In all probability, this action is effective at greater depths.

The size of the shoal or bank formed by the reduction of the cone will depend upon the size of the volcanic vent, its activity, and its length of life. In cases where lava accompanies the pyroclastic material or where several vents are located close together, the mound may exist as an island long enough to allow the development of protecting fringing reefs. In this way some mounds may escape the normal fate of single, purely pyroclastic cones.

Coral reefs that appear to have grown on submarine slopes steepened by wave erosion are exposed on a number of small islands in southern Lau. The best examples were found on the islands of Ongea and Fulanga, which are composed entirely of limestone. On both islands fairly thick sections of well-preserved elevated coral reefs are exposed. The reefs are made up chiefly of the molds of lenticular heads of a variety of reef corals, ranging in diameter from a few inches to 2 feet. A few of the flattened heads are tilted, but most of them are in position of growth. Many of the molds are incrusted with layers of calcareous algae; present, also, are a few spines of echinoids and the molds of a number of common reef mollusks. The fossils suggest that the reefs are Pleistocene in age. The parts of the reefs that are exposed are less than 100 feet in ver-

[11] "Foundations of Coral Atolls," *Nature*, Vol. LV (1897), p. 392.

tical thickness, and there is evidence indicating that the reefs have little width. They appear to form a veneer on steeply inclined surfaces of an older limestone that, on Ongea at least, appears to be Tertiary in age. These veneering reefs appear to have developed on an unusual type of platform. It is interpreted as a submarine slope steepened by wave erosion following elevation, but it may also be interpreted as a steeply dipping platform formed by the submergence of a limestone coast comparable to those that border Ongea and Fulanga today.

The eastern side of the island of Eua in the Tonga group is composed of a series of terraces separated by nearly vertical cliffs. The platforms have been made by marine erosion on foraminiferal limestone of Eocene age. The outer edges of most of the terraces have been veneered by coral reefs of Pliocene age.

PLATFORMS OF DEPOSITION

*Pyroclastics.*—The way in which the waves, aided, to a small extent, by fluvial agencies, reduce a pyroclastic mound to a shoal or submarine bank has already been described in the case of Falcon Island. In that instance the cone was isolated and so small that it could be completely truncated by the agents of erosion. Wave erosion and deposition in such a case make a platform that could be veneered with tuffaceous limestone, later by pure limestone, and finally by coral reefs. Even after reefs have become established on such a foundation, deposition continues to play an important part in widening the margins of the platform. Calcareous debris from the reef is deposited as talus on the sides of the platform. This is a very important feature of platform evolution, because through its action the reef platform continues to grow laterally, regardless of other events.

If the waves attack two pyroclastic cones located close together, an elongated or double platform may be formed. It is believed that many elongated atolls and those showing a distinct figure-eight outline may have foundations of this type. The single barrier reef that encircles the islands of Mothe and Karoni in Lau may be cited as an example. In this particular case one of the volcanic centers was much larger than the other, and apparently it was never completely truncated by the waves.

Irregularly arranged volcanic vents may yield platforms that are almost equally irregular in outline. In this connection the Yangasá cluster in southern Lau may be mentioned. This group of four Tertiary limestone islands is enclosed by a somewhat irregular lagoon, 7 miles in diameter. The regularity of the leeward side of the lagoon is broken by a tonguelike indentation of water, a mile wide at its base and nearly a mile wide at its tip, with a measured depth in excess of 800 feet. There is no evidence to indicate that this deep indentation is a drowned valley, as earlier workers supposed. It appears to be more satisfactorily explained as an area that has been low from the beginning—an area between vents that neither volcanic action nor deposition has succeeded in building to the level of the areas on either side. An irregularity of a different sort is found on the windward side of the Yangasá platform. On this side a reef patch, comparable in size to the leeward tongue, is tied to the seaward margin of the main platform. In our opinion, this almost isolated reef patch probably has a foundation of volcanic material that issued from a separate vent.

*Limestones.*—A remnant of a coral reef that developed upon a foundation

of bedded Tertiary limestone may be seen on the island of Namuka-i-Lau. Namuka is a small, isolated island whose volcanic core is assumed, as no part of such a core now crops out at the surface. In Lower Miocene time the core of the island was blanketed with limestone to a depth of 200 feet or more. The presence of distinct cross-bedding in the lowest layers now exposed suggests that the beds did not accumulate at great depth, but it is equally apparent that corals did not play an important part in the formation of the deposit. These bedded limestones are composed chiefly of Foraminifera and algae. The bank of limestone eventually reached the zone of coral-reef growth and served as a foundation for reef limestone. The form and total thickness of this reef are not known, as only a remnant is now preserved. This remnant, 75 feet in thickness, is found on the upper slopes of Vuniwaro, highest point on the island, and is located on a ridge that parallels the north coast. The section is well exposed on the south side of Vuniwaro, and the reef structure may be clearly distinguished. Molds of dozens of coral heads may be seen; and these, with rare exceptions, are in positions of growth. The heads are elliptical or flattened in section and are small to medium in size, though one colony exceeding 3 feet in diameter was noted.

*Fluvial sediments.*—Reefs may, under favorable conditions, develop upon a foundation of sediments that are largely, if not entirely, fluvial in origin. Examples from the large island of Vitilevu in western Fiji may be cited in this connection.

At Walu Bay, on the southeast side of Vitilevu, a thin lenticular mass of coral-reef rock is included in the marls of the Neogene Suva formation. The colonies of reef corals range in size up to 2 feet in diameter, and an overwhelming proportion of them seem to be in positions of growth. This little reef developed on a foundation of well-rounded pebbles and boulders of volcanic, plutonic, and sedimentary rocks, together with waterworn coral heads and mollusk shells in a matrix of tuffaceous shell rubble. The well-rounded shapes of the cobbles and their lithologic variety suggest river action, an impression that receives support from the occurrence of worn shells of river mollusks.

Nearly one-third of the 4,000 square miles of Vitilevu is drained by the island's largest river, the Rewa. Its drainage area is underlain chiefly by fine tuffs, marls, and lateritized volcanics. The stream, which is very sluggish in its lower reaches, has built a large delta, composed entirely of fine sediments. This delta, still being extended seaward, would seem unfavorable for coral-reef growth; yet reefs do fringe the delta and apparently are growing on sediments brought down by the river.

A thin fringing reef (now dead) that developed on sediments similar to those of the Rewa delta may be seen on the shore of Vitilevu at a point 1 mile south of the post office at Suva. This reef, now somewhat eroded, is exposed at low tide and is more than 400 feet wide near the edge of the lagoon. In general, it trends N. 15° E.; but, as it approaches the land, it curves almost due north and ends on shore a few rods from the old Fiji Museum building. The reef rests directly upon the gently dipping marls of the Suva formation which crop out on the tidal flat between the reef and the shore. A dead fringing reef, very similar to the one south of Suva, is found on the north shore of Suva harbor. According to the late W. A. Set-

chell,[12] a reef of this same type was encountered in constructing a dock in Suva; after boring for a distance of about 20 feet, the drills suddenly went through into softer muds.

PLATFORMS MADE BY VOLCANIC ERUPTION

The fact that crater rims tend to be circular in outline and the fact that atolls likewise exhibit this tendency led early investigators to the conclusion that the reefs of many, if not all, atolls were growing on the rims of volcanic craters. Theoretically, at least, it is possible that some atolls have developed in this manner, but the theory demands some very special conditions. These are so unusual that, in our opinion, the process can be of little importance quantitatively.

The only crater rims that could function as reef foundations without modification by erosive agencies would be rims of resistant lavas. Submarine crater rims of this sort would have to be built to close specifications—namely, volcanic action would have to cease permanently when the rim reached the shallow zone of reef-coral growth. If the crater rim were built above sea-level, subsidence would be necessary to lower it into this same restricted zone. Such conditions may have been met in some instances, but we are unable to cite any specific examples. To us, it seems more reasonable to explain the annular form of most atolls and barrier reefs in terms of ecological conditions. The margins of submarine platforms are favored areas for the growth of reef organisms and in most cases are built up more rapidly than the central areas.

The importance of volcanic action in forming banks of pyroclastic material has already been discussed.

[12] Written communication, 1931.

PLATFORMS MADE BY EARTH MOVEMENTS

Platforms suitable for coral-reef growth have been made by downwarping of coastal lands, by slow uplift of the ocean floor, and by faulting. As previously noted, the embayed northeast coast of Vitilevu is bordered by a well-developed submarine platform 5 miles in width. Patches of reef are growing on this surface, which clearly appears to have been submerged during recent geological time.

The barrier reef of the island of Lakemba in southern Lau may be cited as an example of a reef that probably was brought into the zone of coral-reef growth by uplift. Lakemba is a subcircular mass of andesite, 5.5 miles in diameter. Its central high point rises 720 feet above sea-level. The island is encircled by a fringing reef; and on the east a barrier extends outward to enclose a lagoon comparable in size to the island itself. The lagoon reaches a maximum depth of 14 fathoms, but large areas are exceedingly shallow.

Miocene limestones overlie part of the island's volcanic core, forming an almost continuous coastal belt around the western two-thirds of the island. In general, the limestones become thicker and their belt of outcrop broader to the west, the highest limestone being found on the leeward (northwest) side, where a castle-shaped mass reaches an elevation of 320 feet. The limestone is clearly younger than the volcanic rock, as beds near the contact are filled with volcanic waste, including well-rounded pebbles. The limestone contains a few corals, but no extensive reefs have been found. Following the deposition of the limestone in the Miocene, the island was elevated; and the eastern part of the volcanic mound, though still submerged, was brought within the zone of reef-coral

growth. Continued erosion removed most of the limestone from the windward side of the island; but a fringing reef grew up along the shore, and a barrier developed around the submerged eastern portion of the mound.

What appears to be an example of a barrier reef growing on a platform of limestone formed by faulting is seen in the little island of Komo in eastern Fiji. This unusual occurrence is more fully described in a general report on the area now in press, only the essential features being cited here.

Komo is partly encircled by an oval lagoon, on the leeward side of which there is a well-developed barrier reef. The greatest diameter of the lagoon is about 5 miles. The island, lying on the windward side of the lagoon, is elongated in a direction roughly at right angles to the axis of the lagoon and is nearly 2 miles in length.

At least 75 per cent of the rocks exposed on Komo appear to be volcanic agglomerates, but associated with them are flows and dikes of solid igneous rock. Physiographically, the island is unusual in two respects: (1) it lies on the windward side of its lagoon; (2) its leeward (northwest) coast is straight and cliffed. In our opinion, the leeward coast was formed by faulting, the island on the southeast having been elevated relative to the lagoonal area. The following evidence supports this interpretation: (1) The dips on the bedded agglomerates exposed along the cliff are all high to the northwest, whereas those on the southeast part of the island are gentle and appear to be initial dips. (2) Near the northeast end of the island—along the line of the postulated fault—a series of rocks, including flows and calcareous agglomerates and conglomerates, are greatly disturbed. (3) The trend of the cliff is a continuation of an established fault that cuts the islands of Kambara and Wangava to the southwest of Komo.

On the southwest end of the island and immediately to the northwest of the postulated line of faulting, remnants of limestone are found close to sea-level. These limestones appear to be foraminiferal and show no trace of coral-reef structure. No diagnostic species were collected, but the rock is lithologically identical with that from near-by Karoni, where Miocene (Tertiary *f*) Foraminifera were obtained. The preservation of these limestone remnants on the leeward side of the present island indicates quite clearly that the rock was once more widely distributed. In the past it may have covered much, if not all, of the area now occupied by the lagoon.

After due consideration of all available data we are led to postulate the following as the main steps in Komo's geological history: (1) building of a volcanic cone, largely by pyroclastic action; (2) veneering of this cone with calcareous (re-worked) agglomerate; (3) deposition of foraminiferal limestone, probably below the limit of reef-coral growth; (4) uplift, accompanied by faulting, which raised the southeast side higher than the northwest side; and (5) erosion by marine and subaerial agencies. This latter action removed any limestone that may have existed on the southeast side and removed practically all that may have projected above sea-level on the northwest side. On the platform thus formed on the northwest, reef organisms grew, and a reef was built to sea-level around the margins. The greatest depth of the lagoon is now only 17 fathoms. The existing island on the southeast may possibly represent a segment of the original crater.

## QUANTITATIVE IMPORTANCE OF PYROCLASTIC ACTION

Before leaving the subject of platform formation we should like to stress the quantitative importance of pyroclastics in the islands of the Pacific.

### KNOWN OCCURRENCES

In many volcanic areas of the world, pyroclastic action appears to be unimportant, merely marking the waning stages of volcanic activity. This, however, does not seem to have been the case in the coral-island area of the Pacific. In large parts of this region, which contains a greater development of coral reefs than any other area in the world, the explosive eruption which results in pyroclastic material, rather than in lava flows, seems to have been the dominant type for a long period of time, beginning at least as early as the Eocene.

Vitilevu, in western Fiji, is the second largest island in the open Pacific. It has a core of ancient crystalline rocks, but most of its surface is blanketed with a layer of fragmental volcanic material that is largely Tertiary in age. Enormous quantities of pyroclastics were thrown out of linear volcanic vents or lines of individual vents. The eruptions resulted in mountains that are several thousand feet in height and are composed almost exclusively of agglomerate. Genetically associated with the agglomerates are great thicknesses of tuffs. Over large areas both types of material were reworked by waves or streams before coming to final rest. During this process much clay from weathered volcanic rock and much calcareous shelly material was added, so that many of the rocks are marls.

The smaller islands of Lau in eastern Fiji exhibit a dominance of pyroclastic action that is similar in all essential features to that of Vitilevu in the western part of the group. As might be expected, the re-worked tuffs so widely developed on Vitilevu are practically absent on the small islands of Lau. In the numerous places where the volcanic cores of the islands are exposed, they seem, almost invariably, to be composed of agglomerate.

Most of the limestone islands of Tonga do not exhibit a volcanic base but on Eua such a core is exposed. It is composed of agglomerates and tuffs containing marine fossils and is overlain by a limestone that is Eocene in age. The pyroclastic action of Falcon in Tonga has already been mentioned.

Thicknesses of pyroclastics comparable to those of Fiji have been reported by Mawson from the New Hebrides. Like those of Vitilevu, the deposits in the New Hebrides appear to be Miocene in age.

More recent examples of pyroclastic activity may be seen in White Island, an active cone in the Bay of Plenty near the northern end of New Zealand, and in the historic eruption of Tarawera on North Island. The latter volcano, situated along the line of the great Whakatane fault, erupted violently in 1886. In less than four hours a rent was opened that split the mountain and continued in a northeast-southwest direction for a distance of nearly 9 miles. This tremendous fissure—in places more than a mile wide and nearly 1,000 feet deep—engulfed two lakes; and the pyroclastic ejecta buried villages, but no flowing lava reached the surface. The fissure is still largely open. It and the bordering mantle of pyroclastic material form one of the most impressive exhibits to be seen anywhere; yet, had this event oc-

curred in the open sea, the waves might soon have obliterated most traces of the action.

### ASSUMED OCCURRENCES

The recognition of the quantitative importance of pyroclastic action in the Pacific offers a new explanation for one of the features of this coral-reef area that has helped to shape major coral-reef theories. Over vast areas in the Pacific there are no high-standing islands; only low islands and reefs occur, and this fact impressed those workers who attempted to explain the origin of the reefs. Darwin recognized that isolated islands rising from the deep sea must have a volcanic base, but he was unable to believe that all of these numerous cones could be built to just the proper level for reef growth and then conveniently stopped. Such a proceeding would be a violation of the law of probability. Darwin therefore postulated slow subsidence, accompanied by reef growth. This combination provided a leveling process which he believed was adequate to explain the existence of low-lying islands over wide areas.

The advocates of the Glacial-Control theory believe that the peculiar conditions of the Pleistocene were largely responsible for this phenomenon. As we have shown, however, there are grave objections to both the foregoing general theories, even though both do explain the occurrence of low islands.

The recognition of the widespread occurrence of pyroclastic rocks in the Pacific lends support to the assumption that many of the uninformative low limestone islands are built upon pyroclastic foundations. This explanation requires only explosive volcanism and wave action—it demands neither the extensive subsidence of the Darwinian type nor the unusual conditions of Pleistocene glaciation.

## FORMATION OF THE REEF ON THE PLATFORM

Submerged platforms, whatever their origin, are potential foundations for coral atolls and barriers. Outlined below are several stages in the formation of an atoll from what is probably the commonest type of base, the pyroclastic mound.

### VENEERING WITH TUFFACEOUS LIMESTONE

The surfaces of wave-formed pyroclastic banks would be fairly smooth. Some would lie below a depth of 30 fathoms, the limit of flourishing reef-coral growth; others would lie closer to sea-level within the depth limit of reef-building corals.

The surfaces of the deeper platforms would be suitable places for the growth of calcareous algae, Foraminifera, echinoids, and other organisms that are capable of living at greater depths than are the reef corals. The first deposits on the newly formed platform would, therefore, be a mixture of the skeletons of such organisms and re-worked volcanic material. The exposed cores of many Pacific islands exhibit deposits of this type; numerous examples can be seen in Lau.

### DEPOSITION OF LIMESTONE BY ORGANISMS OTHER THAN CORALS

As deposition continues, the volcanic core may be entirely covered by a deposit of pure yet noncoral limestone. This rock would be composed largely of the skeletons of algae and Foraminifera, together with the shells of mollusks and

the spines of echinoids. Limestones of this type are found in many geologic sections in Fiji.

### FORMATION OF CORAL ATOLL

In time, these noncoral deposits may build the platform upward to the zone of reef-coral growth; and reefs may develop, as they may have developed on platforms that originally lay at this level. Owing to the abundance of food and to other favorable ecological conditions, the corals that settle near the margins of the platform will have an advantage, and these areas will grow upward more rapidly than the central part. Thus an atoll may be formed.

It is believed that the steps outlined above could occur without any change whatever in sea-level. The steadily rising sea-level postulated by the Glacial-Control theory might stimulate reef growth but would not be essential for it. It therefore follows that reefs of the barrier and atoll types were formed in pre-Pleistocene times. The elevated Pliocene barrier reef of Eua, Tonga,[13] is a good example of one of these.

### SUMMARY

The Antecedent-Platform theory states that any bench or bank that is located at a proper depth in the coral seas is a potential coral-reef foundation and that, if ecological conditions permit, a reef may become established and grow to the surface. In this simplified form the theory is all-inclusive. It offers an adequate explanation for fringing reefs, barrier reefs, and atolls that may be developing today or may have developed at any time in the past. Changes in sea-level caused by a subsidence of the land or by a rise of the sea are admissible but not essential. Subsidence of the land furnishes platforms for reef growth, but a slow subsidence of the Darwinian type (subsidence exactly equalized by reef upgrowth) is not required. The theory holds that the shifting sea-levels of the Pleistocene probably stimulated reef development but were not a prerequisite to the development of barriers and atolls.

Platforms suitable for reef growth have been formed by erosion, deposition, volcanic eruption, and earth movement. Examples of all types are found in Fiji and Tonga, some being visible beneath elevated reefs, others inferred beneath existing reefs.

One of the commonest methods of platform-making in Fiji and Tonga—and perhaps in many other coral reef areas in the Pacific—involves wave action on mounds of unconsolidated pyroclastic material. Falcon Island, an active cone in Tonga, is an excellent example. Field investigation indicates that in Fiji and in much of Tonga pyroclastic action has been the dominant type of volcanic activity since early Tertiary time, and it is probable that many of the low coral islands are pyroclastic banks or shoals veneered with reef limestone.

Submarine banks of pyroclastic material that are formed below a depth of 30 fathoms, the limit of flourishing reef-coral growth, are first veneered with tuffaceous limestone. When the volcanic core has been covered by such sediments, pure limestone, composed largely of the skeletons of Foraminifera and algae, are laid down. These noncoral deposits build the platform into the zone of

[13] Hoffmeister, "Geology of Eua, Tonga," *Bernice P. Bishop Mus. Bull. 96* (1932).

reef-coral growth. Corals settling near the margin of the platform grow upward more rapidly than those in the central part. In this way an atoll may be formed.

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# FOUR PHASES OF GLACIATION WITH ILLUSTRATIONS FROM SOUTHWESTERN BRITISH COLUMBIA

N. F. G. DAVIS[1] AND W. H. MATHEWS
University of British Columbia Vancouver, B.C.

ABSTRACT

Glaciers and ice sheets can be classified into four types, or phases, ranging from alpine glaciers, in which the depth of ice is small in comparison to the relief of the land surface, to continental glaciers, in which the depth of ice is much greater than the relief of the land surface. In the former case the direction and rate of flow of ice are determined very largely by the topography; in the latter, by the climate. The characteristic erosion forms of each of the four phases are described, and suggestions are offered as to their origin. Illustrations of the various erosional features are taken from southern British Columbia, and a few typical glacial-erosion histories are outlined.

## INTRODUCTION

### GENERAL

The action of ice in shaping land forms is described in most modern texts under two headings: "Alpine Glaciation" and "Continental Glaciation." Under "Alpine Glaciation" is discussed the modification of mountain and valley forms by the movement of ice down mountainsides and along pre-existing water-worn channels. Ice action is localized, and erosional features are predominant. Under "Continental Glaciation" is described the modification of large areas of land surface by the movement of vast sheets of ice, many thousands of square miles in extent, such as the Greenland and Antarctic ice sheets. Ice action is widespread, and depositional features are usually predominant. Older texts included a third type of glacier, the "Piedmont" or "Confluent" type, formed by the junction of a number of valley glaciers into a single broad mass of ice moving away from a mountain front. The Malaspina Glacier of Alaska is an existing example. A study of the topographic features of southwestern British Columbia has, however, led to the conclusion that glaciation in this region cannot be adequately described by reference to the two or three classic types.

In the following pages, therefore, four types or "phases" of glaciers are defined, and their typical erosion forms, as recognized in southwestern British Columbia, are described. In addition, suggestions are offered as to the origin of these erosion forms, based on a hypothesis of ice erosion which will be given in detail at some later date. In brief, this hypothesis assumes that the rate of ice erosion is dependent, to a very large extent, on the basal velocity of the glacial ice,[2] which, in turn, varies directly as the surface gradient of the ice and inversely as its "viscosity." Low viscosity and high basal velocities are considered to be favored by depth and by an absence of incorporated rock fragments. From a comparison with the flow of liquids, it is also concluded that, other things being equal, basal velocities are higher over convex surfaces, such as ridges and hilltops, than over concave surfaces.

[1] Deceased.

[2] Fridtjof Nansen (*The Strandflat and Isostasy* [Kristiania: I kommission Los J. Dybwad, 1922], p. 21.) believes that "the erosive power of a moving glacier increases approximately with the third power of the velocity of the motion at the underside."

### PHYSIOGRAPHIC REGIONS OF SOUTHWESTERN BRITISH COLUMBIA

The mainland of southwestern British Columbia comprises three physiographic provinces. From west to east they are: the Coastal Trench, the Coast Mountains, and the Interior Plateau. The Coastal Trench is now partially depressed below sea-level, and during the Pleistocene it was mainly an area of deposition. The Coast Mountains are carved by water and ice erosion from a great, upwarped land mass, which, in its southern part, rises to elevations of from 8,000 to 10,000 feet along a central axis lying from 75 to 100 miles inland. The Interior Plateau, beyond the eastern front of the Coast Mountains, stands at an elevation of from 4,000 to 6,000 feet, and its gently undulating surface is cut by trenchlike valleys 2,000–3,000 feet deep.

The topographic features in these three regions display a great variety of ice-produced forms. This variety can be attributed to variations in size and thickness of the Pleistocene glaciers and ice sheets, as well as to variations in the stage of erosion reached by the ice. These variations can, in turn, be attributed to two basic factors, the climatic conditions and the topography, both regional and local. An analysis of the forms has suggested a fourfold division of ice activity, based on the relationship between the thickness of ice and the relief of underlying topography.

## PHASES OF GLACIATION

### DEFINITIONS

The first phase of glaciation is defined as that in which relief of the land surface greatly exceeds ice thickness. This phase corresponds to the alpine type of glaciation. Ice movement is controlled almost entirely by topography.

The second phase is that in which relief slightly exceeds ice thickness. Topography to a large extent still controls ice movement as the ice moves along buried valleys between exposed nunataks.

The third phase is that in which ice thickness slightly exceeds relief. The ice forms a continuous sheet, but the underlying surface continues distinctly to influence direction and velocity of movement.

The fourth phase is that in which ice thickness greatly exceeds relief. In this phase, corresponding to continental glaciation, topography has little control over the general movement of the ice. Instead, the distribution of snowfall, warm air currents, etc., determines the source and fronts of the ice sheet.

It may here be pointed out that the four phases of glacier development outlined here correspond closely to those described by F. A. Kerr[3]—the "Alpine," the "Intense Alpine," the "Mountain Ice Sheet," and the "Continental Ice Sheet"—but have been defined on a different basis.

Periods of widespread glaciation have occurred many times and in different parts of the world. Initiated by climatic factors, the ice sheets wax, wane, and finally disappear. The four phases defined are progressive stages in the growth and decline of ice sheets. The first phase is the initiation of glaciation, and the second, third, and fourth phases may follow in succession. Then, as the ice sheets retreat, the first three phases may be repeated in the reverse order. All four phases have not necessarily existed

[3] "Glaciation in Northern British Columbia," *Trans. Royal Soc. Canada*, Vol. XXVIII, Sec. 4 (3d ser., 1934) pp. 17–32; "Quaternary Glaciation in the Coast Range, Northern British Columbia and Alaska," *Jour. Geol.*, Vol. XLIV (1936), pp. 681–700.

in any particular area. Often, conditions have permitted development only to the first, second, or third phase. The fourth phase has, indeed, been developed typically only in regions of low relief, though often adjacent to mountainous land in which one of the other phases existed.

It should be noted here that the duration of each phase in a sequence varies under climatic controls and that the degree of maturity of erosion during each phase varies accordingly.

### CHARACTERISTICS

*First phase.*—In the first phase of glacier development, mountain glaciers and small valley glaciers are numerous. Ice fields straddling a divide and drained by two or more distributory valley glaciers are rare. On the whole, each stream of ice moves independently of all others.

Cirques, horns, U-shaped valleys, and hanging valleys are characteristic erosional forms of this phase.

*First-phase erosion.*—In a valley glacier the surface gradient and the rate of ice erosion are automatically adjusted to the volume of ice flow and to the size of its channel. Wherever the glacier enters a part of its channel too small to accommodate conveniently the volume of flow, the surface gradient increases. Above any such constriction the ice is dammed back and its surface raised. As the slope to the lower part of the glacier increases, the increasing velocity of ice movement becomes high enough to dispose of the excess ice accumulation. At the constriction the erosion is accelerated, and, in time, the channel is enlarged enough for the ice flow to be accommodated with little or no increase in gradient and velocity.

Where a glacier enters a broader part of a valley or debouches onto an open plain, the surface gradient is reduced. At such places the rate of erosion is correspondingly decreased. In some cases deposition of morainal material may take place beneath and at the front of the ice, thus tending to reduce the size of the glacier channel.

The ice surface at the junction of a tributary to a larger glacier must rise to, or above, the level of that of the main stream. As a result in many, perhaps most, cases the tributary valley becomes flooded to a depth much greater than it would have assumed had the larger glacier been absent. The surface gradient of the lower part of such a tributary glacier is, therefore, materially reduced and, with it, the rate of erosion. If the main ice stream is only slightly larger than its tributary, it too will be dammed back until such a time as the more rapid erosion below the junction, brought about by an increased gradient, enlarges that part of the channel and relieves the congestion. Thus both channels will be narrower and shallower above the junction than below it. If, however, the main stream is very much larger than the tributary, its gradient is not materially affected and the erosion of its channel continues apace. Given sufficient time, therefore, the main channel becomes deepened with respect to the flooded tributary channel until a hanging relationship of the valley floors is developed. Where, because of rejuvenation of preglacial streams or for some other cause, the tributary valleys were already hanging with respect to the main valleys, the surface gradients and rates of erosion of tributary and main ice streams may be nearly equal, and the hanging relationships are maintained.

It should be recognized, therefore, that glaciers, like rivers, tend to adjust the widths and depths of their channels by erosion, and, perhaps less often, by

deposition, to a size comparable to the volume of the streams passing through them. Again, like rivers, glaciers tend to adjust the level of their channel floors until the surface of the stream attains a graded longitudinal profile. It is at the uppermost parts of a valley glacier that the accumulation of snow and the growth of the ice stream are greatest. There the width and depth of the glaciated channel should increase rapidly, giving rise to a "down at the heel" long profile that is characteristic of so many maturely glaciated valleys. Farther downstream near the snow line the ice stream remains nearly constant in size; so should the width and depth of its glacially eroded channel. Finally, toward the snout of the glacier, the ice stream dwindles, and the depth of the channel should decrease.

FIG. 1.—Valley of Stryen Creek, east fork, Lytton. A valley extensively modified by ice of the first phase.

Convex bottom surfaces favor higher bottom velocities than do concave surfaces and are less suited structurally to resist plucking and abrasion. Erosion on projecting spurs, ridges, and shoulders is, therefore, in general, more rapid than in intervening hollows, and a U-shaped trench with smooth and uniformly concave walls should be produced (Fig. 1).

In the above paragraphs have been outlined some of the general characters that should be found after mature erosion by glaciers of the first phase. One significant factor—viscosity—will influence the rate at which this stage of maturity is reached. Near the head of a glacier, rock debris at the base of the ice is scant, and viscosity, as a result, is low. There rapid erosion, probably largely by plucking, is favored. Toward the snout of the glacier, rock debris in the lower layers is concentrated, and the viscosity may be so high that the base of the ice is almost or completely stagnant, and erosion is, therefore, minimized. As a result of this effect, maturity of ice erosion should be most rapidly achieved in the upper parts of a glacier channel; there overdeepening by ice should first become apparent. It is believed, too, that as a result of the increase in the temperature, and perhaps also of the increase in pressure, at depth within the ice, viscosity is decreased. Ice motion and erosion should, therefore, other things being equal, be most rapid at depth. Mature erosion forms should first appear on the floor of the glacier channel. This effect would, in addition, favor deepening of the channel rather than widening and might thus accentuate the hanging relationship of a shallow tributary valley over the deeper trunk valley. Almost certainly, however, rock structure can also influence the relative rates of downward cutting to lateral widening.

It has already been recognized that U-shaped cross sections, truncated spurs, overdeepened channels, and hanging valleys, together with associated alpine forms partly of subaerial origin, cirques, horns, aretes, and cols, are characteristic of areas where the first phase of glacier development has persisted long enough to permit mature erosion.

*Second phase.*—In the second phase of glacier development, mountain and val-

ley glaciers unite to form great, branching glacier systems, many miles long and several thousand feet deep. In general, these glacier systems follow the lines of drainage established by the preglacial rivers. In places, however, the river valleys are not able to discharge all the ice accumulated within them, and it pours across low places on the dividing ridges from one valley to the next. These secondary distributaries cut U-shaped channels or "through valleys" and give rise to a "reticulate" valley pattern never developed by river erosion.[4] In this phase extensive ice fields drained by two or more glacier systems are numerous. The glacier tongues no longer possess the independence of those of the first phase; an unusually heavy accumulation of snow in one place may be dispersed across large ice fields and by "through valleys" to many distributaries (Fig. 2).

FIG. 2.—Homathko ice field from Mount Grenville. An ice mass of the second phase. Photo by Don Munday.

The outstanding erosional features of this phase are heavily glaciated trunk valleys, similar, except in size and length, to the maturely eroded valleys of the first phase, and "through valleys."

*Second-phase erosion.*—Erosion in the second phase closely resembles that of the first, but with one or two important differences. Many of the trunk glaciers head in extensive ice fields which drain in several different directions. At the center of these ice fields motion and erosion at the base of the ice are almost nil. Evidence of this absence of erosion is difficult to find. At different stages in advance and retreat these centers of zero motion shift or disappear, and active ice moves over places once occupied by stagnant ice. However, over a considerable area on the east side of the Coast Mountains there is such evidence.[5] There traces of widespread glaciation are very distinct up to an elevation of about 6,500 feet. Above this elevation there are on south-facing slopes only smooth surfaces mantled with talus of local origin. Till and erratics are lacking. Yet a few miles to the east, in the Interior Plateau, is indisputable evidence in striae and erratics that ice moved parallel to the eastern front of the Coast Mountains,

[4] J. A. Bancroft, "Geology of the Coast and Islands between the Strait of Georgia and Queen Charlotte Sound, B.C." *Geol. Surv. Canada Memoir 23* (1913); J H. Bretz ("Physiographic Studies in East Greenland," in "The Fiord Region of East Greenland," Louise A. Boyd, *Amer. Geog. Soc. Spec. Pub. No. 18* [1935]) has described similar "through valleys" in the Franz Josef and King Oscar fiord complex and has ascribed to them an identical origin.

[5] This evidence is most noticeable in the area between Lytton and Taseko Lake, lying between the crest of the Coast Mountains and its eastern margin (Fig. 3).

crossing ridges over 7,500 feet in elevation. It must be concluded that the ice rose to a corresponding height within the mountains. The absence of erosion and deposition on the south slopes can be attributed to stagnation of ice at the center or axis of an ice field as described above.

The development of the "through valley" is, perhaps, the most important way in which the erosion of the second phase differs from that of the first. It has already been pointed out that rising ice

FIG. 3.—Roach Mountain, Lytton, from the south end of Stryen Creek valley, showing the smooth slopes unaffected by the stagnant ice of the second phase. Mountains in the right background were overridden by glaciers in the last ice age.

streams may "flood" across low places on their banks to pour down with high velocities to adjacent valleys which are empty or contain but little ice. In spite of the shallow depth of ice in these secondary streams where they cross the divides, they are apparently capable of enlarging the original gaps with great rapidity, just as does a river on breaking through a levee. As erosion increases the size of a gap, the ice level of the first valley is lowered, the level in the second is raised, and the surface gradient of the connecting ice stream is reduced. This reduction would, however, be compensated for in part by the increase in the depth of the ice stream, and rapid erosion could continue. The enlargement of the gap may continue, although more slowly, even when the ice levels in the adjacent valleys become nearly equal. Although ice erosion across dividing ridges is thus initiated on earlier weathered or stream-worn gaps, the development of the "through valley" can be regarded as essentially the work of ice.

Markedly different ice levels in adjacent valleys are rarely found except on the flanks of a mountain system. The Coast Mountains have been carved from an upwarped area in which the maximum elevations occur along the central part. Under climatic conditions sufficiently severe, all the valleys of this region would be occupied by ice to about the same level. The smaller valleys at the flanks of the system, because of the smaller basins of accumulation and, perhaps, too, because of lower elevations, might contain but little ice, whereas the longer valleys heading in the high central region would at that stage in their course have become filled and overflowed. It is, therefore, at the flanks of the system, rather than at the center, that "through valleys" are to be expected. In the Coast Mountains that is where virtually all are found.

In the first phase, the ice is generally confined to the mountains or mountain valleys, but, in the second, ice tongues often protrude from the mountain system onto the adjacent plateau, lowland, or continental shelf. These ice tongues, no longer confined to narrow steep-walled valleys, expand into broad but shallow piedmont bulbs, which, as has been pointed out, are much less capable of erosion than the valley glaciers from which they originate. If erosion within the valleys persists, their floors might be lowered in places many hundreds of feet

below the level of the plateau or coastal plain. If such valleys reach the sea, they may become inlets[6] partially or almost completely blocked by a rock bar which may appear as a chain of islets or shoals. Morainal debris may be dumped by the piedmont bulb, further to choke the mouths of the glaciated valleys. A rock bar or a morainal ridge, or both, is characteristic of nearly all the fiords of the west side of the Coast Mountains. In inland areas such obstructions in glacial trenches cause finger- or fiord-lakes.

In the second phase, as in the first, the alpine erosion forms of subaerial origin, cirques and horns, aretes and cols, continue to be formed, though only on the higher peaks free from the almost continuous ice cover.

*Third phase.*—In the third phase the ice sheet is continuous, but the underlying land surface has sufficient relief to influence its direction of movement and to affect its erosion. Although the ice streams are no longer confined by valley walls, the bulk of the flow is still through and above the buried valleys. The greater the depth of ice with respect to relief, the less are the main ice streams deflected by the underlying land forms. Indeed, as the properties of glacial ice become more fully understood, it may be possible to estimate with fair precision the depth of ice which once existed over an area by the amount of deflection of ice streams, as shown by diverging and converging striae, etc., by the topographic features.

In contrast with the second phase of glaciation, in the third variations in climate and regional topography will be more important, and the local topography less important, in determining the direction of ice flow. Also, although major ice streams still exist, they are no longer distinct or limited by nunataks or exposed ridges but grade laterally into one another.

The characteristic erosion forms produced in this phase are glaciated valley floors, domed summits, and rounded ridges.

*Third-phase erosion.*—Erosion in the third phase is limited, but field evidence suggests that it may be appreciable where the ice was thickest, that is, along the floors of the major valleys and at abrupt changes of slope, on summits, ridge crests, and shoulders. Third-phase erosion differs from that of the second phase in three important ways.

First, all parts of the land surface, including peaks and high ridges, are buried under ice. No longer is it possible, as in the second phase, for peaks and ridges to be undercut by ice and scoured by subaerial processes into sharp horns and jagged ridges. Such peaks and ridges, although covered by a shallow depth of ice, are convex surfaces with high rates of curvature, favoring high basal velocities in the ice. They are, therefore, subject to rapid erosion. Soon they are changed from horns and ragged aretes to domed peaks and rounded ridges, the outstanding forms of the third phase (Fig. 4).

Second, surface gradients and velocity gradients are, in general, much less in the third phase than in the second. Several conditions are responsible for these reductions: the ice is no longer confined to narrow streams but may move across valleys, ridges, and plateaus alike; the depth of the ice is greater; and, because of the absence of relief, precipitation is more evenly distributed. The net result of the decrease in gradients is a decrease in the general rate of erosion. Field observations in the southern Interior Pla-

[6] M. A. Peacock, "Fiord-land of British Columbia," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 633–96.

teau give evidence of this. There the ice occupation was almost entirely of the third phase. Except at the bottoms of some of the deeper and longer valleys, evidence of ice erosion is slight. In these valleys, however, the great depth of the ice may have compensated in part for the reduction in gradients and permitted some overdeepening. From the height of the hanging tributaries above the valley floors, this overdeepening amounts at most to only a few hundred feet, as compared with an estimated overdeepening of as much as 2,000 or 3,000 feet in the mountains to the west, where the second phase prevailed for a long time. In a few of the main valleys there is no evidence of glacial deepening or widening. These may have been transverse to the prevailing direction of ice movement.

FIG. 4.—Middle and North peaks of Mount Seymour, Vancouver. A dome mountain, rounded by ice of the third phase.

Third, in this phase the relief conditions for the development of "through valleys" do not exist. It is reasonable to suppose that "through valleys" formed in the second phase would continue to be enlarged in this phase and that marked ice currents crossing high ridges might be capable of producing broad shallow troughs. The amount of erosion would not, however, be conspicuous.

In the third phase there is again a marked difference in the degree of erosion between the source and margin of the ice sheet. Near the ice source in the Cassiar and Cariboo districts of central British Columbia, evidences of ice erosion on the higher ridges is so slight that some observers[7] concluded that they were never covered by ice. This conclusion has, however, been refuted in later reports.[8] Toward the margin of the ice sheet, where discharge and surface gradients were higher, evidence of ice erosion is much more distinct. At the ice front, where discharge is again lower and where the basal ice is brought to near-stagnation by accumulated debris, as in northern Washington, evidence of ice erosion is again less distinct.

*Fourth phase.*—In the fourth phase of glacier development, both hilltops and valley bottoms are deeply buried, and the movement of the ice sheet is little, if at all, influenced by underlying topography. Even regional topography has usually only subordinate influence. The source of the ice sheet lies near the point where excess of snowfall over ablation is greatest. From here the ice moves more or less radially to regions of greatest wastage. Climate, therefore, exerts the dominant control on the movement and distribution of the ice sheets.

The characteristic erosion forms vary with the nature of the underlying rock. Where the rocks are crystalline, numerous though relatively shallow rock-rimmed basins will be found. Where the rocks consist of relatively soft sediments, erosion is apparently confined to smooth-

[7] J. B. Tyrrell, "Was There a Cordilleran Glacier?" *Jour. Geol.*, Vol. XXVII (1919), pp. 55–60.

[8] W. A. Johnstone and Uglow, "Placer and Vein Gold Deposits of Barkerville, Cariboo District," *Geol. Surv. Canada Memoir 149* (1926).

ing and rounding of the pre-existing topography.

*Fourth-phase erosion.*—Conditions in the fourth phase are those of the Continental Ice Sheet. At the center of accumulation the depth of ice may be very great, perhaps two or three times that in any other phase, but surface gradients are very low, only a small fraction of those even in the third phase. At the ice source, therefore, glacial erosion should be almost negligible. Toward the margins the depth of ice is less but the surface gradients higher, and erosion is more conspicuous. Erosion is again almost negligible at the ice front where the depth of the ice has decreased and the heavily laden basal ice is nearly stagnant. This distribution of erosion in an ice sheet is in nearly perfect accord with field observations in eastern Canada, the United States, and Europe.

Where the difference in depth of ice over hills and hollows is relatively small, basal velocity and rate of erosion should be greater over convex surfaces (hills) than over concave surfaces (valleys). Thus the ice tends to reduce the existing relief rather than accentuate it, as in the first three phases of glaciation. Over jointed, crystalline rocks, however, the ice, apparently by plucking, tends to produce numerous small undrained depressions, characteristic of most parts of the Canadian Shield.

In the Coastal Trench, the only part of southwestern British Columbia covered by ice of the fourth phase, ice erosion has been slight. Near Victoria, British Columbia, at the southern end of the trench, evidence of glacial abrasion is widespread, but there is very little in the forms of either the hills or the valleys to indicate ice erosion of more than a few tens of feet during the entire Pleistocene period.

## SUMMARY OF GLACIAL HISTORY IN SOUTHWESTERN BRITISH COLUMBIA

### GENERAL

The land forms over large areas of southwestern British Columbia have a very complex history, for they show not only the results of ice action during different phases of glaciation but also the results of subaerial erosion during glaciation as well as before and after.

### WESTERN COAST MOUNTAINS

The first three phases are illustrated in the western part of the Coast Mountains. Pre-Pleistocene uplift resulted in greatly increased river erosion. Ice later accumulated, and the first phase developed. The second phase followed, and during it the earlier river valleys were widened and deepened by the ice, ridges and peaks were serrated by frost heaving, sapping, and other subaerial processes, and "through valleys" were formed. Then followed the third phase when the original river-cut valleys and the later "through valleys" were still further deepened and widened, while the serrated peaks and ridges were worn down to domes and rounded shoulders. After the climax of this third phase the ice waned, and again the area went through second-phase conditions. The excavation of the main valleys continued while newly formed and semi-independent mountain glaciers re-excavated cirques on the exposed peaks and, assisted by subaerial processes, began re-creating horns and serrated ridges.

During interglacial times the rivers again began their work in the valley bottoms. How much deepening of the valleys they were able to accomplish before ice again occupied the land is difficult to say; but it is possible that they

created V-shaped trenches of sufficient size to confine the later glaciers for a time to a portion only of the earlier glacier floors. The frequent shelves or rock benches well up on the walls of the present valleys may represent the remaining portions of these earlier glacier floors, now modified by later ice.[9]

In the final glacial period the ice rose as high and extended at least as far as in the one or more earlier periods, again burying and rounding the peaks and ridges. After the close of the latest third phase, when the peaks were again exposed by waning ice, local bodies of ice along with subaerial processes again attacked the land surface. On the higher mountains all sides of the peaks were attacked by the mountain glaciers which again produced horns and comb ridges. On the lower mountains only the north and east slopes were attacked by the vigorous local glaciers. Only these slopes were oversteepened, and the resulting asymmetric peaks and ridges now resemble huge sea breakers. The term "wavelike topography" can be aptly used to describe such a landscape (Fig. 5).

FIG. 5.—View west from Roach Mountain, Lytton, showing wavelike topography developed by glaciers of the first phase which existed only on the shady northern slopes. Virtually all the area in the photograph is underlain by granitic rocks. (Photo by Bureau of Geology and Topography, Ottawa.)

In late glacial and postglacial times rivers carried tremendous quantities of finely ground rock from the waning glaciers and deposited it to depths of several hundred feet on the valley floors and at the heads of fiords. Elsewhere rivers have cut steep-walled canyons scores of feet deep in the lips of hanging valleys and across buried rock spurs. In general, however, the streams have yet done little to modify the glaciated appearance of the mountains and valleys.

[9] C. A. Cotton, "Shoulders of Glacier Troughs," *Geol. Mag.*, Vol. LXXVIII (1941), p. 81.

### CENTRAL COAST MOUNTAINS

In the central part of the Coast Mountains, the history is similar to that in the western part, as already described, except that there is no indication of a third phase of glaciation and that "through valleys" are much fewer. In this area, too, the mountains were of sufficient height to allow the development of local glaciers in the final phase on all exposures, and wavelike topography was not developed.

### INTERIOR PLATEAU

Because of their distance from the sea, river valleys in the Interior Plateau were little affected by pre-Pleistocene uplift. During the Pleistocene the main river valleys which afforded continuous channelways for the ice were widened and deepened not more than a few hundred feet. On the retreat of the ice, tributaries of these valleys were left hanging. Since then the hanging valleys have been incised by prominent V-shaped trenches, and the main valleys filled to depths of several hundred feet by fluvioglacial deposits. This stream-cutting and deposition is going on at the present time.

### COASTAL TRENCH

In the Coastal Trench, erosion either by ice or by stream action is not prominent. The Fraser Delta shows evidence of Pleistocene subsidence of perhaps 2,000 feet, combined with sedimentation.[10] On the east coast of Vancouver Island, valleys show little or no modification by ice action, and the coast line there indicates drowning to the extent of several hundred feet.

[10] Johnstone, "Geology of Fraser River Delta Map-Area," *Geol. Surv. Canada Memoir 135* (1923).

# REGIONAL METAMORPHISM IN THE KENOGAMISIS RIVER AREA

R. D. MACDONALD
University of Western Ontario, London, Canada

ABSTRACT

The rocks of the Kenogamisis River area consist of sediments, volcanics, and intrusives. The sediments and volcanics have been regionally metamorphosed to rocks of varying metamorphic grade. The sediments grade from a high of garnetiferous and staurolitic types through biotitic types to a low of chloritic types. Hornblendic volcanics are in equilibrium with the biotitic sediments; chloritic volcanics are in equilibrium with the chlorite sediments. Medium to basic oligoclase is the characteristic feldspar of the higher-grade metamorphics; albite is the characteristic feldspar of the chloritic rocks.

## INTRODUCTION

The Kenogamisis River area is situated to the south of the Little Long Lac area, District of Thunder Bay, Ontario. The area was mapped by the writer for the Ontario Department of Mines in 1939 and is described in Part VII of the *Annual Report of the Ontario Department of Mines*.[1]

The general geology of the area is shown in the accompanying generalized map (see Fig. 1). Granite and related rock types occupy the southern part of the area. The rest of the area is occupied by two belts of sediments and two belts of volcanics that are interbanded with each other. The volcanic rocks include basic to acidic flows and volcanic fragmentals and tuff. The sediments include slate, greywacke, quartzite, micaceous paragneiss, mica schist, and garnetiferous and staurolitic gneiss.

## METAMORPHIC FACIES

The sediments and volcanics have been metamorphosed to schists and gneisses of varying mineral assemblages. The results of this investigation show that the metamorphic mineral assemblages present in the Kenogamisis River area are similar to those described by J. W. Ambrose[2] for the Missi series of Manitoba. For purposes of general comparison, the mineral distributions are plotted in a graphical form similar to the form used by Ambrose (see Fig. 2). The sediments occupy the greater portion of the area and show a wider mineral variation than the volcanics. The volcanics have different mineralogical assemblages from the sediments but compare in metamorphic grade with the sediments that are near them.

### METAMORPHIC FACIES OF THE SEDIMENTARY ROCKS

The sediments can be divided into chloritic, biotitic, and garnetiferous types. They show a general gradation from chloritic types on the north to garnetiferous types on the south. The chlorite zone occupies a belt approximately 2 miles wide that lies to the south of the northern volcanic belt (see Fig. 1). The biotite zone occupies the remainder of the sedimentary area except for the portion occupied by the garnetiferous rocks. Although in part interdispersed with biotitic types, the garnetiferous types lie within $1\frac{1}{2}$ miles of the southern granite mass.

[1] Vol. XLIX (1940).

[2] "Progressive Kinetic Metamorphism in the Missi Series, near Flin Flon, Manitoba," *Amer. Jour. Sci.*, Vol. XXXII (1936), pp. 257–86.

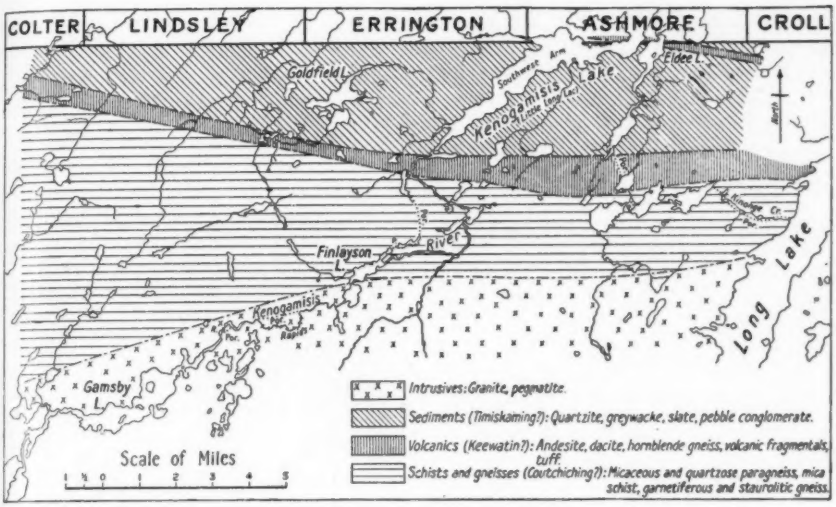


FIG. 1.—General geological map of the Kenogamisis River area

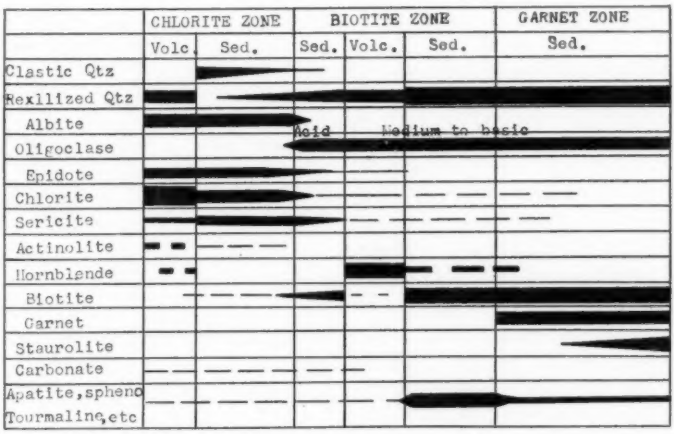


FIG 2.—Graphical representation of the mineral distribution in zones

The general mineral assemblages characteristic of the sedimentary metamorphic types are listed below:

| | | |
|---|---|---|
| Chlorite zone | Quartz-albite-chlorite-sericite-epidote<br>Quartz-albite-chlorite-actinolite-sericite-epidote | ± calcite |
| Biotite zone | Quartz-oligoclase-biotite-chlorite-epidote-sericite- ± calcite<br>Quartz-oligoclase-biotite-hornblende<br>Quartz-oligoclase-biotite | |
| Garnet zone | Quartz-oligoclase-biotite-garnet- ± staurolite | |

THE CHLORITIC ROCKS

These rocks consist of slaty to arkosic greywackes. The minerals present are quartz, albite, chlorite, sericite, biotite, actinolite, calcite, epidote, and metallics. Quartz is the predominant mineral; albite is the feldspar in all sections that are coarse-grained enough to allow optical determinations. Chlorite is present in all sections and is the most abundant of the ferromagnesian constituents. Sericite is also present in all sections; in some cases it is coarse enough to distinguish as muscovite. Calcite[3] is present in all but the very fine-grained rocks. Biotite is present in minor amounts as irregular crystals or as poorly formed porphyroblasts. Epidote and clinozoisite are present as scattered grains in the majority of sections. Apatite and tourmaline are sporadically present as very minor constituents. The common mineral assemblage is quartz-albite-chlorite-sericite-epidote-calcite. Actinolite forms an important constituent in some rocks of the chlorite zone. The main mineral assemblage of this type is quartz-albite-chlorite-actinolite-sericite-epidote-calcite.

[3] The term "calcite" is used as a group name. The indices of refraction of some of the material indicates it to be ankeritic.

THE BIOTITIC ROCKS

Rocks of considerable variety fall within this type, but they are grouped together because they all have biotite as their dominant ferromagnesian mineral. They are subdivided, on a mineralogical and textural basis, into three groups.

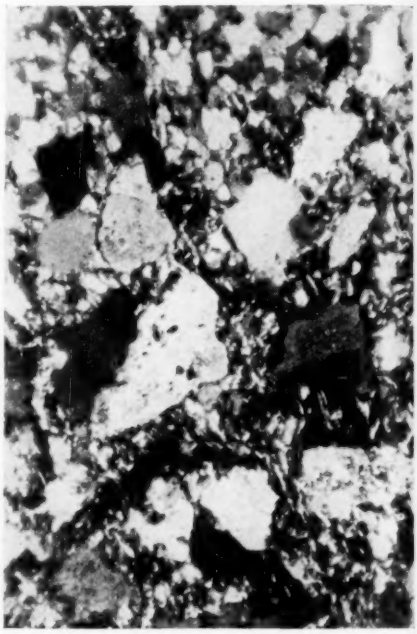

FIG. 3.—Photomicrograph showing the texture of the feldspathic greywacke. Crossed Nicols, × 100.

The groups themselves show a zonal distribution.

The first group includes the sediments lying between the sediments of the chlorite zone and the southern volcanic belt. The rocks are micaceous greywackes that are quite similar in appearance to the coarser greywackes of the chlorite zone, but they usually have a more pronounced schistosity. They consist of quartz, feldspar, biotite, lesser chlorite, sericite, or muscovite, calcite, epidote,

and metallics. The feldspar is an acid oligoclase that is moderately clouded with alteration products. Biotite forms an important constituent and occurs in two modes. The greater portion consists of flakes of brown pleochroic biotite; the other type is in the form of fine interstitial needles and has a pale-green pleochroism and low birefringence. Chlorite and muscovite or sericite are usually present but are in lesser amounts than in the chloritic rocks. Calcite is erratic in distribution; epidote is minor.

The notable mineralogical features of this type are the presence of acid to medium oligoclase, light-green acicular biotite, and moderate amounts of normal biotite. The textural differences between these and the chloritic rocks are shown in Figures 3 and 4. This group shows textural features indicative of a more pronounced reconstitution of the groundmass. Some of the quartz grains appear to retain their original granular shape, but other grains of quartz and feldspar have been broken down to aggregates of smaller units.

The second group of the biotitic rocks is characterized by the presence of hornblende. They are more coarsely crystalline, and in most cases more schistose, than the rocks of the group just described. They occur to the south of the volcanic belt in a zone approximately one hundred chains wide. The mineral constituents are quartz, feldspar, biotite, and hornblende, with lesser sericite, chlorite, and metallics. The feldspar is a medium to basic oligoclase. Pale-green to distinctly pleochroic-green types of hornblende are present. The pale-green types have optical properties indicative of a pargasitic hornblende. An increase in the amount of accessories such as apatite, sphene, and tourmaline is a noticeable feature of the group.

The rocks of the third biotitic group are similar in megascopic appearance to those just described, but they have no hornblende. Inasmuch as the rocks of both units are closely associated, although the nonhornblendic types are more widespread, the difference between them may be due to an original difference

FIG. 4.—Photomicrograph showing the texture of the biotitic greywacke. Crossed Nicols, × 100.

in composition rather than to variations in metamorphic grade. The normal type of this group is a schistose to gneissic rock consisting of quartz, medium oligoclase, biotite, minor chlorite, sericite, and accessories. The groundmass is completely reconstituted and consists of interlocking grains of quartz and feldspar. The feldspar is less clouded than that of the previously described rocks. Biotite usually occurs as aligned plates, but some of the rocks are characterized by coarse porphyroblastic crystals. The

undeformed nature of the porphyroblasts indicates that they developed subsequent to the movements that foliated the rocks (Fig. 5).

### THE GARNETIFEROUS ROCKS

The garnetiferous types are coarsely crystalline schistose to gneissic rocks. Some of them contain staurolite. Except for the presence of garnet or of garnet and staurolite, they are texturally and mineralogically like the coarse biotitic and porphyroblastic types just described. Garnet is more common than staurolite and usually accompanies staurolite wherever it is present. The garnets and staurolites are euhedral, the garnet occurring as dodecahedrons and the staurolite as stubby, prismatic, twinned and untwinned crystals. Quartz inclusions occur in both minerals but are especially abundant in the staurolite. The schistose planes sweep around the garnets and staurolites, but the crystals do not appear to have been rolled. Sericite is minor in some of the feldspar; chlorite is apparently secondary after biotite. Epidote and calcite are rare. Tourmaline and apatite are present in all the garnetiferous and staurolitic rocks. Magnetite often occurs as clusters of small grains (Fig. 5).

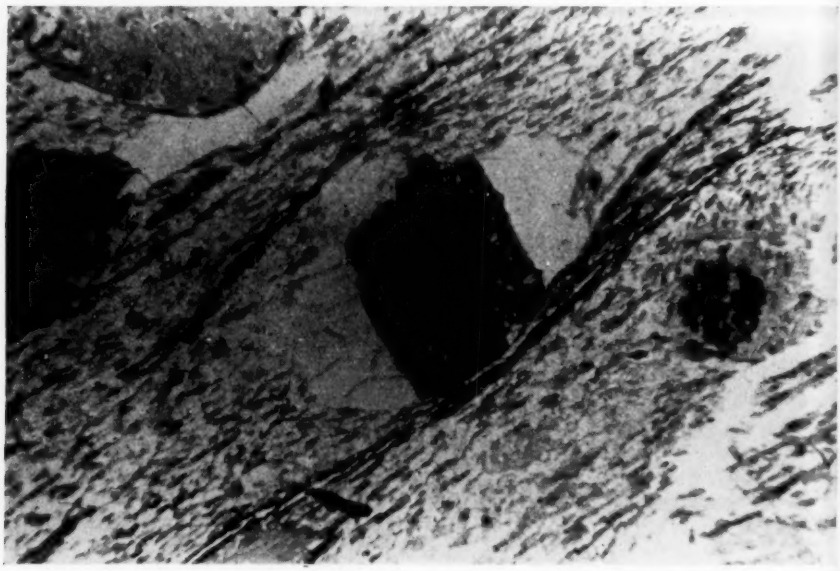

FIG. 5.—Photomicrograph of porphyroblastic biotite schist showing a biotite porphyroblast oriented almost at right angles to the foliation. × 30.

### METAMORPHIC FACIES OF THE VOLCANIC ROCKS

Although the two volcanic belts are too narrow, in themselves, to show differences in their mineral assemblages, there are differences between the two belts that indicate two metamorphic facies. The mineral assemblages coincide in degree of metamorphism with the mineral suites of the sedimentary rocks. The northern volcanics lie in the chlorite zone, and the southern volcanics lie in the biotite zone of the sediments. The

minerals of the northern volcanics are quartz, albite, chlorite, epidote, sericite, calcite, and metallics. Hornblende, actinolite, and biotite are present in some of the rocks. The common mineral assemblages are: quartz-albite-chlorite-epidote-calcite-sericite; quartz-albite-actinolite-chlorite-epidote-sericite; and quartz-albite-chlorite-hornblende-epidote-calcite-sericite.

Quartz is minor in all the rocks. Biotite is a minor constituent in a few of them. F. J. Turner[4] attributes its presence in rocks of this type to an appreciable potash content. The presence of actinolitic rocks probably indicates original chemical differences in the volcanics that resulted in the development of an albite-actinolite-chlorite-epidote assemblage rather than an albite-chlorite-epidote assemblage. Turner[5] considers the actinolite schists to be stable in the low-grade rocks when there is insufficient water to form chlorite and insufficient carbon dioxide to combine with the lime that would be set free in the chloritization of actinolite.

The apparent anomalous feature of hornblende being present in the chlorite zone may be explained in two ways. It is possible that the hornblende may have developed early as a result of chemical reaction between chlorite and calcite.[6] Since, however, the hornblende only occurs in the more coarsely crystalline rocks of this zone, it is probably an original constituent that has not been destroyed during metamorphism. The presence of albite and chlorite in the hornblendic rocks indicates that they belong to the chloritic metamorphic group.

The minerals present in the southern volcanics are quartz, oligoclase, hornblende, chlorite, epidote, and metallics. Sericite, biotite, sphene, and apatite occur as minor and sporadic constituents. While there are variations in the relative amounts of the minerals, the rocks show a marked uniformity in their mineral constituents. They form a hornblende-oligoclase-epidote-chlorite assemblage. The feldspar is usually an acid oligoclase; some is a medium oligoclase. The pleochroism of the hornblende indicates that most of it is an alkalic type. Epidote is not abundant except in some of the coarser-grained rocks; in most cases it is an iron-poor to zoisitic type. The minor chlorite that is present may be material that has not changed in response to higher metamorphic conditions but in some cases appears to be an alteration product of hornblende. The tuffs afford an example of the metamorphic equilibrium of the volcanics with the surrounding sediments. Their mineralogical assemblage of quartz, acid oligoclase, biotite, with lesser chlorite, epidote, and calcite is similar to that of the sediments in the biotite zone.

The rocks of the two volcanic belts show marked textural differences as well as the mineralogical differences just described. These can be seen best in the more coarsely crystalline types and involve a breakdown of the feldspar crystals in the southern volcanic rocks. The feldspars of the northern volcanics ordinarily show a subhedral form (see Fig. 6); those of the southern volcanics consist of finer-grained anhedral mosaics (see Fig. 7).

[4] "The Genesis of Oligoclase in Certain Schists," *Geol Mag.*, Vol. LXX (1933), p. 531.

[5] "Contribution to the Interpretation of Mineral Facies in Metamorphic Rocks," *Amer. Jour. Sci.*, Vol. XXXIX (1935), p. 414.

[6] Turner, p. 531 of ftn. 4 (1933).

FIG. 6.—Photomicrograph showing subhedral feldspar in the coarse andesites of the northern volcanics. Crossed Nicols, × 30.

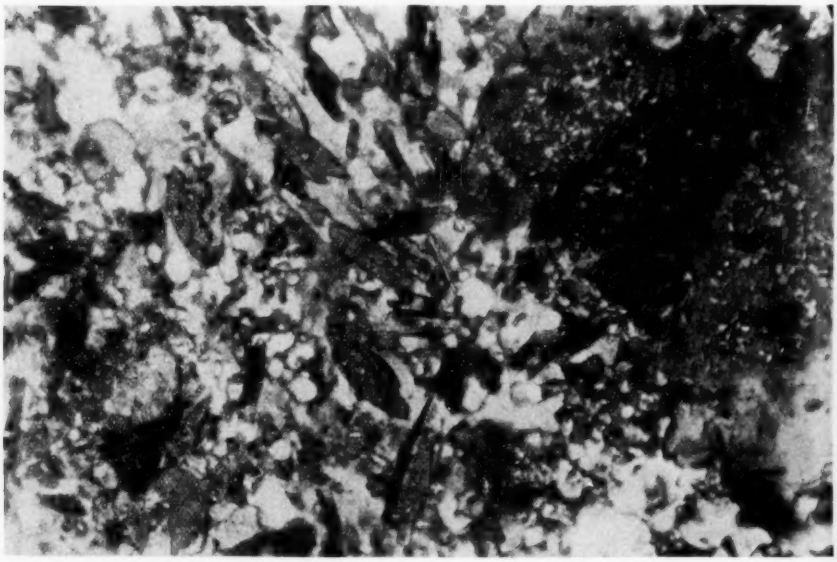

FIG. 7.—Photomicrograph of the texture of the coarse gneisses of the southern volcanics. Porphyroblastic-like hornblende on the right. Crossed Nicols, × 100.

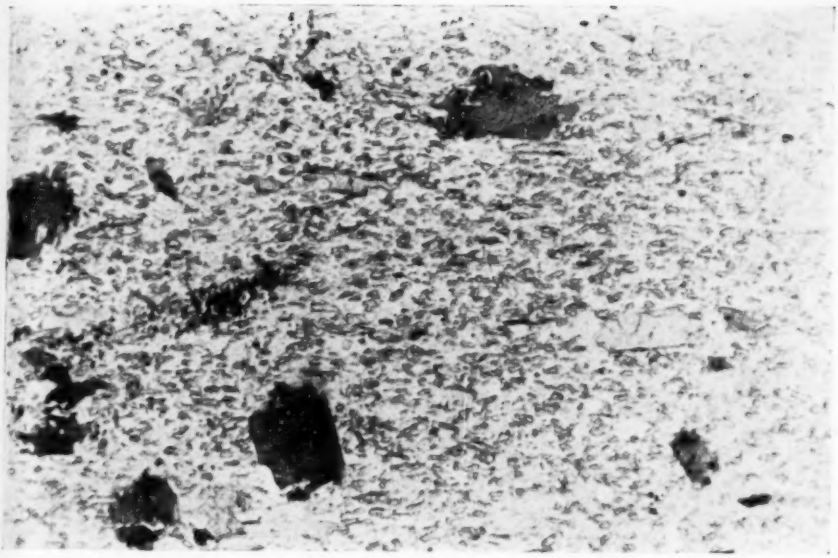

FIG. 8.—Photomicrograph of irregular biotite porphyroblasts in slaty greywacke. × 125

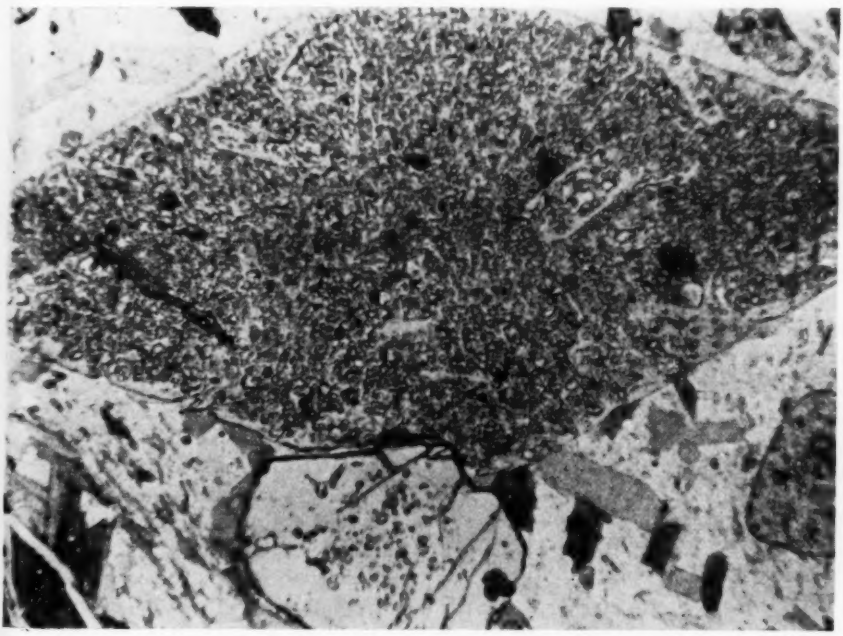

FIG. 9.—Photomicrograph of staurolite and garnet porphyroblasts. × 40

## Causes of Variations within Metamorphic Zones

The metamorphic zoning as described is an interpretation of the general regional metamorphism. Exceptions to this general zoning were noted in the separate zones. For example, rock characteristic of the chlorite zone was found in the southern volcanics and in the southern sediments. Such variations, however, are thought to have been caused by one or more of the following factors:

1. Original differences in composition
2. Variations in the original grain-size of the rocks
3. Variations in the intensity of dynamic action to which the rocks have been subjected
4. Variations in the intensity of thermal metamorphism

The bulk composition of the original rock may affect the subsequent mineralogical assemblage in several ways. Since the development of a mineral depends primarily on the presence of the necessary constituents and their ability to combine chemically, a mineral such as biotite may be unable to form if sericite and chlorite, from which it could form, are present in such small amounts that the two cannot react. Likewise, hornblende might form, rather than biotite, if the rock were high in chlorite and calcite but low in potash.

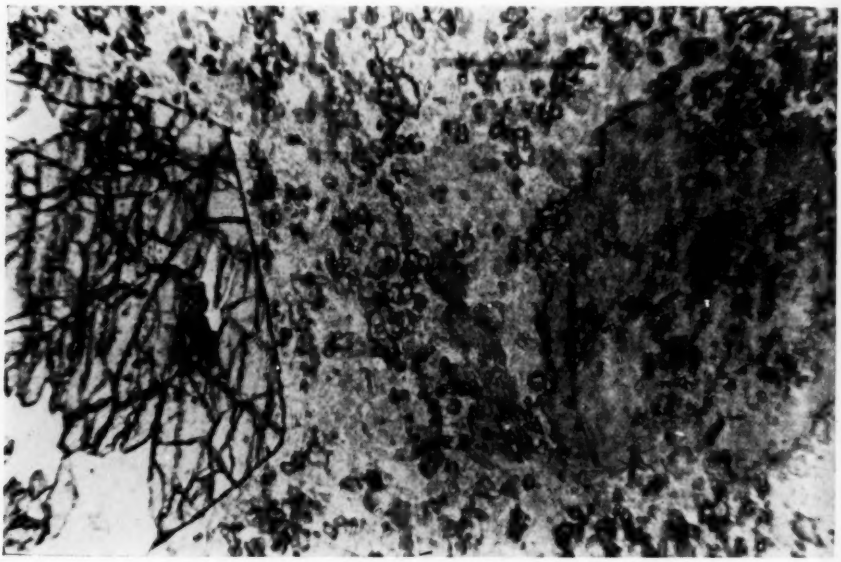

Fig. 10.—Photomicrograph of garnet and chlorite porphyroblasts. The chorite is pseudomorphous after biotite. × 40.

Although the causes may involve more than grain size, it is a fact substantiated by numerous observations that, within the same outcrop, rocks of different grain size often show different mineral assemblages. Staurolite sometimes occurs only in the coarser bands of a garnetiferous gneiss; slaty greywacke with a quartz-feldspar-chlorite-sericite assemblage may occur with a granular

greywacke having a quartz-feldspar-biotite-chlorite-sericite assemblage. Apparently, the finer-grained rocks lag behind the coarser-grained ones in developing the minerals of higher metamorphic grade.

Variations in the effect of dynamic action will be present because of variations in the competencies of the rocks. Although the intensity would generally decrease away from the region of greatest dynamic action, rock differences would cause local variations in the degree of metamorphism resulting from dynamic action.

Thermal metamorphism was more intense in the southern part of the area. The absence of an even gradation in mineral assemblages away from the granite may be due to an irregular roof on the granite. For some distance north of the granite-schist contact its top may not be far below the present land surface. This is indicated by the presence of granitic and pegmatitic dikes in the schists to the north of the granite mass.

## Conclusions

The metamorphic grade reached in the rocks of the Kenogamisis River area is not high. Staurolite is evidently the highest-grade mineral present; no kyanite or sillimanite or their remnants occur. Notable mineralogical differences between the rocks of this area and those of the Missi series in Manitoba[7] are: (1) the presence of actinolite and hornblende in some of the sediments, (2) the lower metamorphic stage at which oligoclase is developed, and (3) the presence of considerable staurolite in the rocks of the garnet zone.

Since bedded structures are discernible in practically all the sediments, dynamic action could not have been extreme. The southern granite mass is considered to have been the main metamorphosing agent; dynamic action is considered to have played a lesser role. This is inferred from the following facts:

1. The more highly metamorphosed rocks occur near the southern granite mass.

2. The presence of considerable tourmaline, sphene, and apatite as accessories in the southern sediments probably indicates the introduction of materials from a granitic source.

3. The postdeformation growth of porphyroblastic biotite, garnet, and staurolite indicates that solutions were active subsequent to dynamic action.

4. Some of the most highly contorted and sheared rocks of the region are those that lie in the Little Long Lac area to the north of the Kenogamisis River area. These rocks are chloritic. Therefore dynamic action alone does not appear to be the controlling factor in metamorphism.

It is the writer's belief that dynamic action produced the channelways through which the metamorphosing solutions traveled and that these solutions, which were the main agents of heat transfer, derived their heat from a magmatic source. The lack of retrograde action in the area can be explained on this basis, since with the cessation of dynamic action channelways would soon be blocked and metamorphic action would rapidly decline.

Acknowledgments.—Laboratory investigation of the rocks was carried out at Princeton University, Princeton, New Jersey. For the help and guidance received from Professors A. F. Buddington, E. Sampson, H. H. Hess, and A. K. Snelgrove and for the use of the laboratory facilities the writer wishes to express his thanks.

[7] Ambrose, ftn. 2 (1936).

# IGNEOUS ROCK AREAS IN THE NORRIS REGION, TENNESSEE[1]

GEORGE M. HALL AND H. C. AMICK
University of Tennessee, Knoxville

ABSTRACT

Two small areas of mica-peridotite occur in Union County, Tennessee, near the "Great Bends" of the Clinch River. They appear to be outcrops of inclined basic plugs that were intruded along or near the plane of a major fault. The magma appears to have been at a low temperature when intruded, as it did not metamorphose the sedimentary rock with which it came in contact. The age of the intrusion cannot be definitely determined. The youngest sedimentary rock cut by the peridotite is the Chattanooga black shale of Mississippian age. Therefore, intrusion was later than the early part of the Mississippian period. These plugs are of special interest because they are in an area that has long been considered a sedimentary province without any intrusions.

## INTRODUCTION

Two small exposures of mica-peridotite occur in Clark Hollow on the southeast side of Lone Mountain. Clark Hollow is located in Union County, Tennessee, near the "Great Bends" of the Clinch River, about 30 miles upstream from Norris Dam, following the meanders of the river, and is approximately 5 miles northwest of Maynardville (see Fig. 1). The name "Clark Hollow" is well known locally, but it is not shown on the Maynardville quadrangle of the United States Geological Survey or on Sheets C9 and 10 of the "Survey of the Tennessee River and Its Tributaries" by the Corps of Engineers of the United States Army. The area of the peridotite outcrops and the immediately adjacent region are shown in Figure 2.

The region surrounding the igneous rocks is underlain by sedimentaries ranging from the Rome formation of Lower Cambrian age to the Chattanooga black shale of Mississippian age. The normal sequence is broken by a fault of great displacement, whose stratigraphic throw of about 7,000 feet brings the two formations just mentioned into juxtaposition. It is a low-angle overthrust which complicates the geology in the vicinity of the peridotite plugs and explains in part the peculiar outcrop pattern of the region. The formations along the major fault have been broken and cut by subsidiary faults in many places, and a spring in Clark Hollow issues from one of these zones of fracturing.

## SEDIMENTARY FORMATIONS

The Rome formation consists of dark-brown, yellow, green, and red shales, with a large amount of dark brown sandstone at the base, and in places lenses of nonfossiliferous limestone. The formations between the Lower Cambrian and the Silurian are not exposed in Clark Hollow, having been cut off by the fault; but they are well exposed in adjacent areas. Lone Mountain is largely composed of Silurian shales and sandstones, but fragments of iron ore (Clinton or Rockwood) are common along the channel of the small stream that drains Clark Hollow. Hancock dolomite appears in contact with the peridotite and for several miles in either direction along the fault, although at most places the dolomite is concealed by debris from the Rome or Silurian formations, making it

[1] Published by permission of the Tennessee Valley Authority. Dr. G. M. Hall died in 1941, and the manuscript has been revised by the junior author.

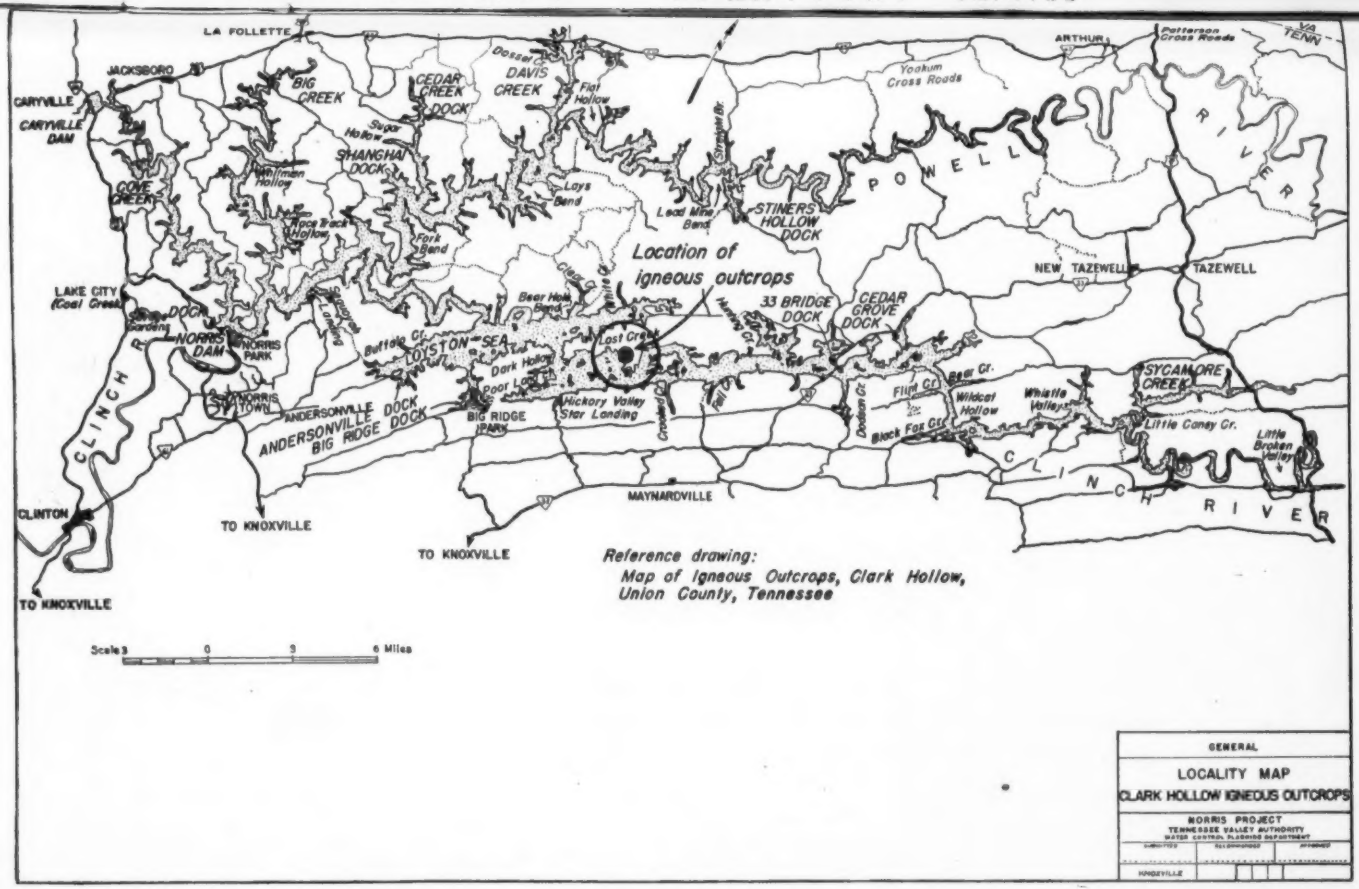


FIG. 1.—Norris area. The circle shows the location of the igneous outcrops

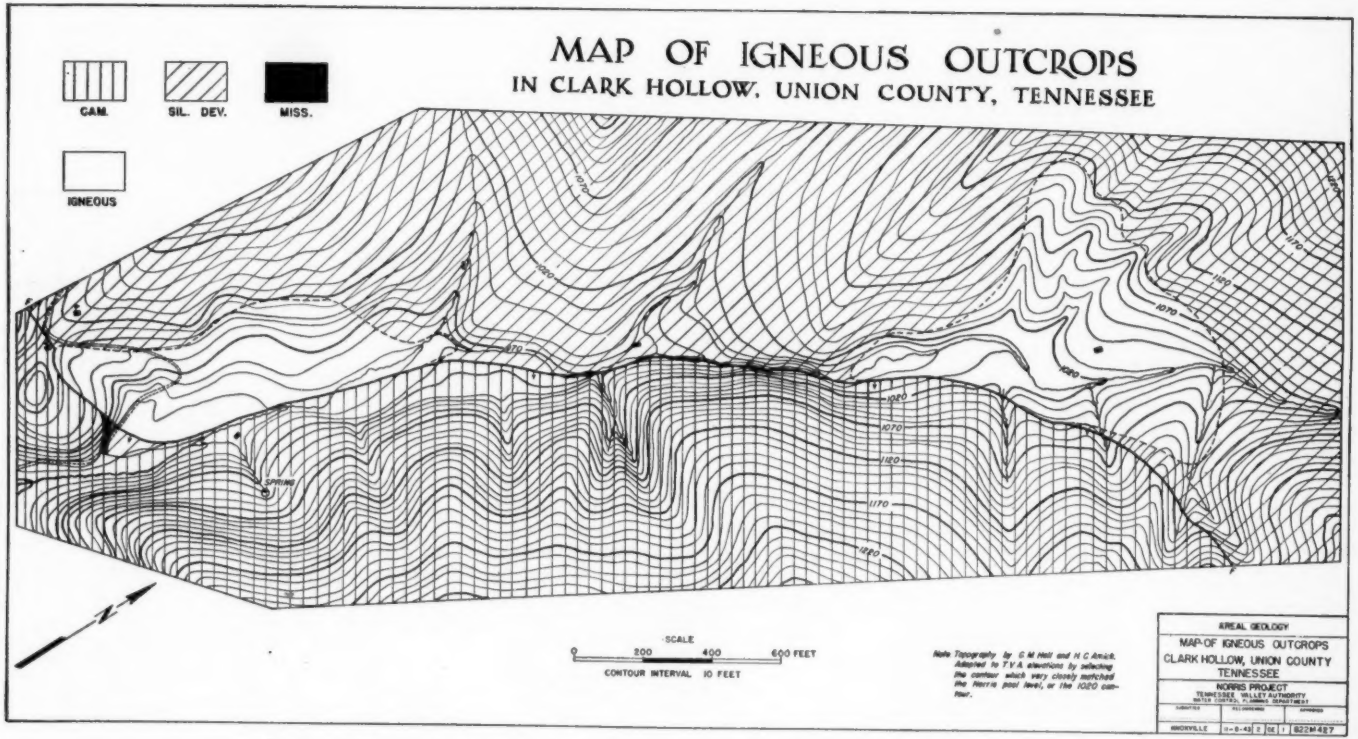


FIG. 2.—The 1,020-foot contour represents the elevation of Norris Lake when the reservoir is full

impossible to determine its thickness or its exact relation to the overlying sandy beds from which fossil collections were obtained. However, the Hancock dolomite outcrops in thick beds approximately 40 miles to the northeast in the vicinity of Sneedville, Tennessee, where it was studied by Arthur Keith, who considered it to be Devonian in age. Subsequent determinations by other investigators show that this dolomite contains strata of both Silurian and Devonian age. In the immediate vicinity of the northeastern peridotite plug the following fossils (some of which came from loose blocks of sandstone that lie in great profusion over the surface) were collected:

*Favosites helderbergiae*
*Platycrinus* sp.
*Aspidocrinus scutelliformis*
*Nucleospira elegans*
*Delthyris* sp., probably perlamellosa
*Rhipidomella oblata*
*Stropheodonta* sp.
*Calymene clintoni*
*Liocalymene clintoni*
*Geisonoceras* sp. cf. *G. imbricatum*
*Leperditia elongata willsensis*
*Bonnemaia* sp. cf. *B. transita*

These fossils were identified by Dr. Charles G. Butts, of the United States Geological Survey. The assemblage is in part Devonian and in part Silurian. The Chattanooga black shale overlies the Hancock dolomite and is exposed in a limited crescentic band. No fossils were found in it; but, like the typical Chattanooga, it is very black on fresh surfaces, weathering to a rusty brown with yellow streaks. It is the youngest formation in contact with the igneous intrusives.

Particularly striking is a brilliant green, medium-grained sandstone, probably a part of the Hancock formation, which occurs in contact with the northeastern plug. Its appearance suggests metamorphism by the intrusion, but microscopic examination of the rock disproved this interpretation. The unusual green color is due to the presence of clay minerals[2] and not to any influence of the mica-peridotite.

## THE IGNEOUS INTRUSIONS

The mica-peridotite was first described by J. M. Safford[3] as a gray-green metamorphic rock of limited extent in Union County, Tennessee. He noted the presence of magnetite within it. Later it was called to the attention of Dr. C. H. Gordon, of the University of Tennessee, by a local prospector who had dug several prospect pits in the outcrops in search of precious metals. Dr. Gordon recognized the true nature of the material but did not complete the investigation, because of failing health. He published a brief abstract of his study in the *Bulletin of the Geological Society of America*.[4] After his retirement and death, further work was undertaken by the present writers.

The mica-peridotite occurs in two small areas which extend about 3,000 feet in a northeasterly direction and are separated by an outcrop of Hancock dolomite. A well-drilling contractor, employed by a local prospector to test the southwestern outcrop, reported that he drilled through the igneous material and into the underlying sedimentary rocks in less than a hundred feet,[5] which suggests an inclined plug. This fact, together with the location of the outcrop

[2] C. S. Ross, oral communication.

[3] *Geology of Tennessee* (Nashville: S. C. Mercer, Printer to The State, 1869), p. 175.

[4] "Mica-Peridotite Dike in Union County, Tennessee," Vol. XXXVIII (1927), pp. 125–26.

[5] J. E. Morris, oral communication.

alongside the prominent low-angle thrust fault, makes it appear probable that these are inclined plugs that were intruded along the fault plane or through the fractured rocks of the fault zone.

The rock of the southwestern plug is somewhat broken or brecciated, while that of the northeastern has a pronounced banding that conforms to the regional strike and dip, which might suggest that it was exposed to at least a part of the forces which distorted the sedimentary rocks of the region. Numerous inclusions of Hancock dolomite have been found in both plugs. In some places they form agglomerate masses, showing that the magma was injected into broken zones or tore its way through, rounding the fragments of the dolomite. Igneous material filling lines of weakness, such as joints and bedding planes, was observed at several places in the Hancock dolomite area, which lies between the plugs. However, at the time of its intrusion, the temperature of the magma was not high enough to assimilate the calcareous rock. Except for a slight hardening, the fragments do not appear to have been metamorphosed by the intrusion (see Fig. 3). B. C. Moneymaker, chief geologist of the Tennessee Valley Authority, collected fossil crinoid stems from the area that have peridotite filling the center openings and spaces between the segments, but the segments themselves show no signs of alteration.

Some of the accessory minerals of the mica-peridotite are worthy of comment. Excellent crystals of magnetite were collected from the weathered material on the surface of the northeastern plug. Some of these crystals show the usual octahedron form, while others are combinations of the cube, rhombic dodecahedron, and octahedron. When crushed, the material from both plugs is attracted by a magnet, which shows that fine grains of magnetite are also present. However, the material from the northeastern plug is attracted more vigorously than that from the southwestern. Light- and dark-colored garnets occur in both areas. The lighter colored ones are largely $Mg_3Al_2(SiO_4)_3$ with only a trace of iron. The darker ones are much richer in iron and appear to approximate more nearly the formula $(CaMg)_3(AlFe)_2(SiO_4)_3$. They are usually rounded, although the lighter, more transparent variety appears to be in less rounded masses than the more opaque type. The peridotite has much carbonate material distributed through it. The southwestern plug, in particular, has been cut by veins of ankerite with thin dense centers of strontianite. A pale-green to yellowish-white waxy mineral, probably deweylite, forms shiny irregular masses and vein fillings in the peridotite. It appears to be an alteration product with a composition approximately the same as a low-iron-content serpentine. In places this mineral surrounds crystals and fragments of magnetite.

Thin sections of the peridotite show that the olivine is thoroughly serpentinized and that a large amount of calcite has been deposited throughout the rock. Biotite masses are partly weathered and bleached. Opaque minerals, such as magnetite and ilmenite, are very abundant—some are in crystal form but most of them are in the form of irregular grains. The banding previously mentioned is more conspicuous under the microscope than in hand specimens.

Recognition of the peridotite intrusions soon led to several suggestions. It seemed possible, at first, that they might constitute the source of the volcanic ash (meta-bentonite) beds of Ordovician age which are widespread over eastern Ten-

nessee and parts of some of the adjoining states. However, these intrusions could not have been associated with the ash beds, for the following reasons. First, the mica-peridotite plugs are composed of ultra-basic rocks, while the ash beds are highly acid. Second, the intrusions cut the Chattanooga black shale of Mississippian age and, therefore, could not have been the source of Ordovician ash beds. The intrusions are younger than the Chattanooga black shale; but how much younger cannot be determined, because there is no means in the area of dating them at a later time.

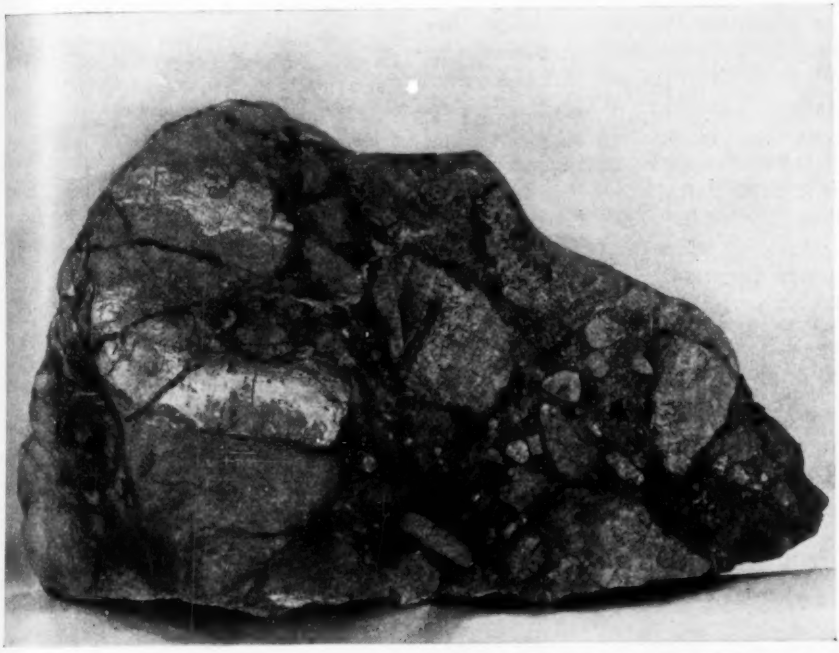

FIG. 3.—Photograph of a specimen from an outcrop between the upper and lower peridotite plugs near the contact of the peridotite with the Hancock dolomite. It shows the igneous material filling spaces between broken pieces of dolomite. (About ½ natural size.)

Since diamonds have been found associated with the peridotite intrusions in Arkansas and other parts of the world, the writers carefully examined the igneous-rock outcrops and the gravel bed in the lower part of Clark Hollow; but no diamonds were found. Nevertheless, two diamonds were found about 1904 by fresh-water pearl fishermen, in gravel deposits near Hickory Creek Shoals on the Clinch River, a short distance downstream from Clark Hollow, near the present site of Hickory Star Landing. They were purchased from the pearl fishermen by Mr. Harry Curtis, a Knoxville jeweler,[6] who reports them to be blue-white and of good quality. The larger of the two diamonds weighed about 3 carats in the rough and produced a cut stone that weighed 1¼ carats. The

[6] Oral communication.

smaller one weighed about $\frac{7}{8}$ carat in the rough and produced a cut stone that weighed $\frac{3}{4}$ carat. Both stones are now in the possession of a prominent Knoxville family.

After devoting considerable time to the study of the peridotite intrusions of Clark Hollow, both in the field and in the laboratory, the writers visited intrusions of comparable material in the vicinity of Murfreesboro, Arkansas, and Marion, Kentucky. While similarities were observed, no information was acquired that could be used in a more definite correlation of the Clark Hollow plugs. For some years there has been a tendency to relate the mineralization in eastern Tennessee to an igneous source, but without any important outcrops of the parent material. These Clark Hollow intrusive bodies thus become suggestive. In any case, the plugs in Union County are igneous masses in an area which has long been considered a sedimentary province without any intrusions.

ACKNOWLEDGMENTS.—The writers wish to acknowledge their indebtedness to Dr. Charles Butts, of the United States Geological Survey, for identifying fossils; to Dr. C. S. Ross and Dr. Hugh D. Miser, for their criticism in the field; and to Dr. Ross, for his study of the slides made of the Union County, Tennessee, and the Marion, Kentucky, rocks. Mr. B. C. Moneymaker, chief geologist for the Tennessee Valley Authority, and Dr. R. Lee Collins, of the Geology Department, University of Tennessee, have also rendered valuable assistance in criticizing the manuscript and in offering constructive suggestions.

# REVIEWS

*Eruptive Rocks*. By S. JAMES SHAND. 2d ed. New York: John Wiley & Sons; London: Thomas Murby & Co., 1943. Pp. xvi+444; pls. 3; figs. 47. $5.00.

After much delay incident to war conditions a second edition of Professor Shand's *Eruptive Rocks* has finally appeared, a welcome addition to the growing number of texts on igneous petrology. The arrangement of subject matter is almost identical with that in the first edition, which appeared in 1927, but there is a significant expansion of the text which reflects the growth of knowledge in the intervening years as successfully as is to be expected within the limits of a small volume.

In an introductory chapter the author discusses the general nature of the rocks which he prefers to call "eruptive" rather than "igneous" and gives reasons for this preference, which the reviewer finds none too convincing even while fully recognizing that some igneous magmas have transitional relations to aqueous solutions. No single term can be properly inclusive and exclusive as applied to such complex materials, and "eruptive" is no exception. Sandstone dikes, some of them at least, are eruptive rocks but how different and how drab as compared with the igneous rocks which the author discusses.

The constituents of igneous rocks are now described under the designations, "fixed" and "fugitive." The separation into these two classes has much practical value and must find its justification therein, for in detailed analysis the same lack of rigid distinction is again found. The water and fluorine which escape from a magma into surrounding rocks are fugitive, yet the water and fluorine which crystallize from the same magma as components of hornblende or mica are fixed. In this connection the author registers objection to the reviewer's proposal of the term "hyperfusible." It is true that no advantage for this term can be claimed in the matter of offering a clear-cut division of the magmatic components into classes, but this is not the basis of objection. The term was proposed to emphasize the presence in magmas of certain constituents which, by virtue of their own low melting temperatures, act as powerful fluxes in the magma. The purpose was to stress their character as fluxes during the orthomagmatic stage when they enter into the magma in precisely the same manner as any other constituent. This end could be accomplished only by avoiding such terms as "volatile" and "fugitive" which stress certain characters that some part of these constituents may later acquire with the progress of crystallization of the magma. Each term has advantages for a specific purpose. The reviewer is unable to grasp the basis of objection to "hyperfusible." The author even states that the dissolved gases of the magma are not low-melting substances. In other words warter, carbon dioxide, fluorine, and such substances are not low-melting materials!

In a following chapter some of the thermal properties of various rock constituents are reviewed and a geologic thermometer scale based on them is given as a preparation for a discussion of the freezing of the complex mixture known as a magma. This discussion is very brief, yet it succeeds in presenting the salient features of equilibrium studies applicable to the crystallization of magmas and leads naturally to a discussion of the action of a magma on the wall rocks with which it makes contact. Here is presented a good summary of actual observations and of theoretical interpretations of the mutual effects of magma and wall rock and their possible consequences in bringing about the variations observed in igneous bodies. The extent to which variation can occur without such extraneous chemical influence and the possible causes of such spontaneous variation are discussed in a chapter on "Eruptive Rock Complexes." The whole subject of the causes of variation comes in for still more detailed discussion after the author presents his favored classification of igneous rocks and passes on to describe and discuss the various classes. One class may emphasize, according to current opinion, processes of origin that are of but little import in connection with another class. The reader will therefore find, under oversaturated rocks, a discussion of the present-day revival of ancient views of the origin of granite by replacement processes; under another class, discussion of the origin of peridotites through

accumulation of olivine crystals and such modifications of this view as have been suggested for special cases, as, for example, to account for certain great masses of serpentine; under yet another class discussion of the problem of the origin of the alkaline rocks which reveals the author's strong predilection for the limestone-syntexis hypothesis. For the most part, however, these discussions reflect current views and do not strongly emphasize the author's preferences.

The author's moderation in thus presenting the problems of the origin of the various classes is not matched in his presentation of the actual classification itself. In a general discussion of classification the author flays existing classifications and nomenclature. The reader cowers in anticipation of a whole system of new names but is relieved to find only the old familiar ones and their number reduced to a minimum by the use of modifying terms. Most petrologists will be pleased, too, that the broad basis of classification is mineralogical and modal. Not so generally acceptable is the prime importance assigned to saturation with silica as a basis of major subdivision, for it leads to the description of such unrelated types as dunite and corundum-bearing rocks in the same chapter and requires the description of basalt with a little free quartz in a separate chapter from basalt with a little olivine, though the author, in his chapter on "Eruptive Rock Complexes" recognizes their intimate genetic association in a single igneous body. Few petrographers will accept the author's separation of diorite from gabbro on the basis of the proportion of dark minerals. Separation based on the nature of the plagioclase is almost universally accepted and has much to recommend it on genetic grounds. None of these features of classification is new to this edition. Plainly the author stands by his guns.

In introducing each major topic, the author has used an epigraph. It is the irony of fate that, for the chapter which discusses the genesis of feldspathoidal rocks, he should have hit upon "A theory is a tool and not a creed" (J. J. Thomson). Blind faith in a theory—the limestone-syntexis theory of the genesis of feldspathoids—finds clearest expression in this chapter in the statement, "It cannot be too often repeated that the absence of outcrops of limestone is no proof of its absence in depth, especially among Archaean rocks." Limestone syntexis is one mode of origin of feldspathoidal rocks. It has been demonstrated in one locality, the Scawt Hill area of County Antrim. Yet the acceptance of this process for any area where the evidence is somewhat favorable is only delayed by insistence on its univeral truth. The author rightly condemns Holmes's processes of "transfusion" by means of "emanations" as the mode of origin of the Lake Kivu leucitic lavas, but limestone syntexis is not thereby rendered a probable alternative. Indeed one cannot fail to find in the Kivu rocks, as Finckh did earlier, much evidence in favor of the close connection, maintained by Holmes, between plutonic biotite peridotite and the leucitic lavas, though one need not accept Holmes's transcendental processes.

Acceptance of the limestone-syntexis hypothesis is not hastened by blind rejection of alternative proposals. This reviewer has suggested that one mode of genesis of feldspathoidal rocks depends upon the incongruent separation of leucite, sometimes with subsequent reaction of the leucite with liquid, the evidence of which may survive in those peculiar structures known as pseudoleucite. The author suggests that the contribution of the sodic phase of pseudoleucite (nepheline) by the soda from the liquid magma is a recent proposal of the reviewer made to shore up the tottering edifice of his theory. Nothing could be farther from the facts; the reviewer has never countenanced any leucite but the purely or almost purely potassic type and has always regarded the nepheline of pseudoleucite as contributed by the liquid simultaneously with its contribution of silica to produce orthoclase from the leucite. The alkaline rocks have undoubtedly arisen as a result of a variety of processes, and proper evaluation of their relative importance is yet to be made.

In his advocacy of one theory of the alkaline rocks to the exclusion of others the author has merely fallen into an error to which all flesh is heir, and he should not be accused of an undue general tendency in that direction, especially by this reviewer. His treatment of his subject as a whole is well balanced. The petrologist will find the book useful, thought-provoking, and eminently readable.

N. L. B.

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